

*PROGRESS REPORT
ON
INVESTIGATION OF NUCLEAR
MOISTURE-DENSITY METERS*

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*Joint
Highway
Research
Project*

*PURDUE UNIVERSITY
LAFAYETTE INDIANA*

*by
STAFF MEMBERS
OF THE
SOILS LABORATORY*

Progress Report

INVESTIGATION OF NUCLEAR MOISTURE-DENSITY METERS

TO: K. B. Woods, Director
Joint Highway Research Project

January 30, 1963

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 6-10-5
Project: C-36-16E

Attached is a progress report on the Nuclear Moisture-Density Project. This report was prepared by personnel in the Joint Highway Research Project Soils Laboratory.

The paper is for the information of the Bureau of Public Roads and the Indiana State Highway Commission. It summarizes work done up to this time on three instruments. These instruments are designated by trade name in the report.

Copies of the report should be transmitted to the Bureau of Public Roads. In particular, Mr. Preston Smith would like several copies for review. Mr. W. T. Spencer should also receive a copy for review.

Respectfully submitted,

H. L. Michael

H. L. Michael
Associate Director

HLM/ike

Attachments

cc: F. L. Ashbaucher
J. R. Cooper
W. L. Dolch
W. H. Gostz
F. F. Havey

F. S. Hill
G. A. Leonards
J. F. McLaughlin
R. D. Miles

R. E. Mills
M. B. Scott
J. V. Smythe
J. L. Walling
E. J. Yoder



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Progress Report

on

Investigation of Nuclear Moisture-Density Meters

by

Staff Members of the Soils Laboratory

Joint Highway Research Project

File No.: 6-10-5
Project No.: C-36-16E

January 30, 1963

ACKNOWLEDGMENTS

The work reported herein was carried out in the Soils Laboratory of the Joint Highway Research Project. The work was done under the supervision of Professor Eldon J. Yoder.

Mr. Alfonso Burgers conducted all of the initial tests on the Nuclear-Chicago Instrument. He conducted the tests on the heavy liquids.

Mr. Matthew Witozak is currently conducting the tests using three different nuclear gauges. He is responsible for tests on the soils and depth of influence measurements.

Mr. Thomas Williamson prepared the initial draft of this progress report and he also assisted in conducting some of the laboratory tests.

Parts of this report are taken from the MSCE thesis "Influence of Selected Material Properties on Nuclear Determination of Density and Moisture" by Alfonso Burgers.

Progress Report
on
Investigation of Nuclear Moisture-Density Meters

INTRODUCTION

On August 9, 1961, the Joint Highway Research Project Advisory Board approved a plan of study entitled "Investigation of Nuclear Density and Moisture Meter." The purpose of this study was to investigate the use of a commercially available moisture density meter for possible use by the Indiana Highway Commission.

It was proposed to compact soil samples in large containers in the laboratory and test these using the moisture-density meters. The use of the large containers was proposed to facilitate direct measurement of bulk density as well as density using the sand cone.

It was also proposed that extensive studies be made of the instrument in the field. This to be done by taking the instrument to various construction projects and using it to test base course and subgrade materials. These results could then be compared to results achieved by using conventional testing practices.

History of Study

The project, as proposed initially, became effective on September 1, 1961. The project was approved by the Joint Highway Research Board, the Indiana State Highway Commission and the Bureau of Public Roads as a cooperative study using HPS funds. It was decided at that time to test the instrument manufactured by Nuclear Chicago, Inc.

The start of the project was delayed until the latter part of December 1961 due to delay in receiving the instrument. The density probe

was shipped to Lafayette toward the end of December and the moisture probe arrived during the first week of January 1962. Laboratory testing was started immediately upon receiving the equipment.

Mr. C. H. Holmes, then Assistant Commissioner for Research, Bureau of Public Roads, in a memorandum dated June 5, 1961 pointed out that it would be desirable for State Highway Departments investigating nuclear instruments to expand their studies to include an evaluation of other commercial instruments. This memorandum was brought before the project staff who subsequently contacted both the Bureau of Public Roads and the Indiana State Highway Commission concerning the expansion of the original study to include the Viatec and Troxler instruments. A revised working plan covering work on three instruments was approved on February 14, 1962.

It was proposed that these new instruments be purchased and an evaluation made of these devices in the same manner as for the Nuclear Chicago. A correlation of the three instruments was also to be made if possible.

It was proposed to use the instruments in the field during the summer of 1962 as well as during the summer of 1963 if necessary. The results obtained then were to be compared to results obtained using conventional methods. Laboratory calibrations were to be made on all three instruments during the winter of 1962-63 according to the proposal.

PURPOSE AND SCOPE

Numerous factors influence unit weight and moisture measurements obtained by nuclear density and moisture instruments which are independent of the apparatus itself. One of these factors lies in the inability

to determine exact bulk unit weight using conventional volumetric and gravimetric procedures.

It is customary to determine bulk unit weight of a soil in the field by means of the sand replacement, balloon, oil or other similar methods. Volume measurements by the above methods are somewhat variable, and they are inconvenient due to the protracted period required to produce reliable results. The nuclear density and moisture meters were developed for the purpose of speeding up field testing and for producing greater accuracy in measuring unit weight and moisture.

Permanent high quality standards covering the normal range of soil densities and moisture contents and which can be used for checking the nuclear instruments are difficult to obtain. These standards must permit establishing a calibration curve of density versus count and pounds of water versus count, but in addition are used to check the continued reliability of the density gauge over extended periods of usage.

The nuclear instrument itself introduces several variables due to: (a) the emission characteristics of the radio-active source, and (b) the transient behavior of the electrical components of the machine. The transient behavior results from ambient conditions and aging effects of the detector tubes and radio-active source.

The primary purpose of this study is to obtain calibration curves for the three nuclear instruments for both unit weight and moisture content for various types of soil compacted to varying degrees of compactness in molds. The purpose of this phase of the study is to determine if type of material has any effect on the readings, and if high air voids and

2.

degree of saturation effect the measurements. Another consideration involved in this phase is to determine if the type of container in which the materials are compacted has an effect on the measurements. Depth of influence, effect of moisture on density readings, and use of the instruments to determine depth of asphaltic concrete are included in the purpose of the investigation.

A secondary purpose of this study was to investigate the use of liquid standards covering the usual density range (90 to 160 pcf) of soil and aggregate. Experience has shown that it is difficult to produce uniform solid standards, and that solids are liable to change due to atmospheric conditions, especially if used both in the laboratory and the field. On the other hand it is a relatively simple matter to determine the unit weight of a liquid for all conditions.

The need for a homogenous standard is supported by Carey et al (1).

"Single Standard for Over-all System Check:

There are many possible sources of error. It is desirable to check the entire system on a single standard at frequent intervals. This standard ideally should be of a density in the general range of interest and it should be homogenous. A good standard is natural dolomite (a block at least 9 in. thick and 2 ft. square with one smooth plane face is suggested). Concrete is not satisfactory since it is seldom homogenous."

In addition to the advantage of uniformity, by using liquids, the depth of influence and the effect of container size on the readings were easily investigated. This phase of the study was performed using only the Nuclear Chicago instrument.

MATERIALS

Heavy Liquids Studied

The liquids investigated were:

1. Sym-tetrabromoethane ($\text{CHBr}_2\text{CHBr}_2$) (24)

(Specific Gravity = 2.9638, $\frac{20^\circ\text{C}}{4^\circ\text{C}}$)

2. Carbon tetrachloride (CCl_4)

(Specific Gravity = 1.595, $\frac{20^\circ\text{C}}{4^\circ\text{C}}$)

The lighter liquid was tested first. The heavier liquid was then diluted with the lighter to obtain three other unit weights,

During testing the temperature of the liquids was measured and their specific gravities were accurately determined at the same temperature with a volumetric flask. The unit weights at which the liquids were tested were 161.7, 140.4, 120.7, and 99.6 pounds per cubic foot.

Soils Studied

Four soils were tested in this investigation. These were:

1. Sand-soil mixture
2. Dune sand
3. Coarse sand
4. Gravel

Grain size distributions for the four materials are shown in Figure 1. The compaction curves of the materials are shown in Figure 2. Since the coarse sand contained relatively little fines, it was difficult to obtain a reasonably good standard AASHO compaction curve for it. For this reason the compaction curve for the coarse sand is shown as a broken line. The value obtained, however, gives an indication of its compaction characteristics.

Table 1 summarizes the physical properties of the four materials. The specific gravity tests were performed in accordance with the procedure described by Lambe (2) in a calibrated 500 millilitre flask.

EQUIPMENT

Equipment used for the investigation consists of the three nuclear instruments and the various testing equipment required for the calibrations. These are shown on plates 1, 2, 3, & 4. Plate 1 shows the instrument manufactured by Nuclear Chicago Corporation. This instrument consists of:

1. Density surface gauge, model P-22, Serial No. 157; containing a radioactive source Cesium 137, 3 millicuries, with half life of 33 years.
2. Moisture surface gauge, model P-21, Serial No. 161, complete with wax standard; containing a radio-active source radium-beryllium, 4.2 millicuries, with half life of 1620 years.
3. Scaler model 2800A, Serial No. 419. (The scaler is fitted with a timing device which checks with high accuracy against a 0.1 second calibrated stop watch.)

The above equipment is powered with a six volt battery housed in the scaler. The scaler supplies high voltage to the detector stages of the density and moisture gauges. The battery can be charged by an automatic built-in charging unit when connected to an alternating current supply. The equipment can also be operated from an alternating current supply.

Plate 2 shows the instrument manufactured by the Viates Division of Tellurometer, Inc. and includes:

1. Scaler Model HDM2, Serial No. 249 (The scaler is fitted with an automatic timing device.)

2. Hydro-Densimeter Surface Probe, Model SP2, Serial No. 249; containing a Ra/Be radioactive source, 8.14 millicuries.

The above equipment can be powered by an internal battery, external battery, or A.C. power. The high voltage outputs to the Geiger tubes are pre-set in the factory for the particular type of detector tube used.

Plate 3 shows the instrument manufactured by the Troxler Electrical Laboratory. This instrument consists of:

1. Glow-Tube Scaler, Model 200B, Serial No. 39 (The scale is fitted with a Rate Meter for quick measurements or comparisons and an automatic timing device for one minute count intervals).
2. Surface Moisture Adapter, Model 104-115, Serial No. 20; containing a Ra/Be radioactive source, 3 millicuries.
3. Surface Density Gauge, Model SC 120, Serial No. 201; containing a Ra/Be radioactive source, 3 millicuries.
4. Miscellaneous equipment: Model 3-1 Battery Assembly, Model 3-2 Battery Charger and a Model 4-DC to DC Converter.

The above equipment is designed to operate on an internal 18 volt rechargeable battery or from a 115-volt, 60 cycle external power supply.

The remainder of the equipment is concerned with the compaction of the soils and the containers for the heavy liquids. These are shown on Plate 4 and are briefly as follows:

- a. Split mold, 24 inches in diameter by 12 inches high.
- b. Pneumatic sand compactor with a 4 inch diameter rubber tipped foot operating at pressures between 50 to 70 pounds per square inch.

- c. Sheet metal containers, 13 inches high, having diameters 14, 16, 18, 20 and 22 inches, respectively.
- d. Metal stands to hold the density gauge in position at levels varying from one inch above the bottom of each container to 13 inches above this level, advancing by one inch intervals.

Sand replacement density techniques were used to determine the unit weight of the sand-soil mixture. Ottawa sand was used with an average bulk unit weight of 95.8 pounds per cubic foot.

PROCEDURES OF TESTING

Initial Testing with Nuclear Gauges

Preliminary Checks

Initial laboratory testing done during the winter and spring of 1962 was accomplished using the following procedures. All tests with the nuclear density and moisture gauges were conducted using power from the 6 volt battery since this is the method used in the field. Each gauge was first checked to read correctly on the standards provided by the manufacturer. The voltage was adjusted so that each gauge would reproduce an average count within the "reliable error" as determined by the manufacturer's standards.

Basic Testing Procedure

After the completion of the above checking and adjustment of each gauge the instrument was placed on the surface of the material to be tested. These materials had previously been prepared so that no apparent air gaps were visible underneath the sources and detectors of the gauges. Five count readings were then taken and the average of these values used as the count for the material tested. When excessive variations occurred

during a set of five readings, further counts were taken to determine if some spurious cause may have affected the original readings. Usually, the readings which were most nearly consistent with the statistical requirements of 90 percent confidence level were used in setting up the data curves.

Testing of Heavy Liquids

Five containers with diameters ranging from 14 inches to 22 inches were used during the liquid testing phase (Plate 4). Suitable stands were made such that the gauge height could be increased by one inch intervals from the bottom of each container.

Five counts were taken at one minute intervals and the average calculated. This average count was plotted against the depth of liquid for each container.

The liquids were tested using the lightest liquid first and diluting it with the heavier liquid as the testing proceeded to obtain different unit weights.

Testing of Soils

The four soils used for the investigation were compacted with a pneumatic rammer fitted with a 4 inch diameter rubber tipped foot. No particular effort was made to relate this compactive effort to standard AASHO effort, but an attempt was made to obtain uniform compaction throughout the depth profile of the soil.

Sand-Soil Mixture

The sand-soil mixture was thoroughly mixed with the required amount of water, placed in closed containers, and allowed to stand for a period of one day. The material was then compacted in the 24 inch split mold using eight 1.5 inch layers.

The top layer was then used as the testing surface and the average of five nuclear readings for both density and moisture was then determined with the Nuclear-Chicago gauges. Immediately following this, the unit weight of the soil was determined using a 6 inch sand cone. A separate moisture content sample was taken from the density hole.

Gravel, Coarse Sand and Dune Sand

Difficulty was experienced in determining the unit weight of the gravel and sands by means of the sand replacement method. It was therefore decided to determine the bulk unit weight of these materials by weighing and measuring the volume of the entire sample. All three materials were tested when completely dry, saturated, and at several intermediate moisture content conditions.

For both the dry and saturated states, the procedures consisted of placing the material in as loose a condition as possible by pouring the soil from a constant height above the leveled surface and then vibrating it at the surface and around the sides of the container.

The nuclear density count was then obtained, and the container weighed to obtain the average unit weight of the material both in the dry and saturated conditions. For the saturated material the weight before and after vibration was determined to permit the calculation of average unit weight. On the saturated samples nuclear moisture counts were also determined, but difficulty was experienced during sampling for moisture content determination by drying.

The partially saturated materials were compacted with the pneumatic rammer at different moisture contents. The nuclear density and moisture counts were recorded and unit weights determined as described earlier.

Revised Testing Methods

Upon obtaining the two additional nuclear testing instruments a different testing procedure as compared to the previously described method was initiated.

The three instruments were tested using a constant voltage for each as recommended by the corresponding manufacturers.

All laboratory tests performed during the summer, fall and winter of 1962 were made using power from the batteries in the instruments so as to simulate field practices.

With the presence of the two new instruments in the testing area it was necessary to make a check to determine if their presence had an effect upon the count readings for the instrument being tested. It was decided from this investigation to keep the sources that were not in use behind a concrete wall constructed in the testing area to eliminate the chance of these sources influencing the count readings of the test instrument. Unfortunately, the concrete barrier was adopted only after a large number of tests were found to be in error due to background radiation.

Testing of the Materials

The materials tested were the sand-soil mixture, gravel, and coarse sand as previously described.

Testing of the materials consisted of taking from eight to twelve one minute readings on each test layer. A minimum of two readings were taken with the instrument oriented in four different directions. Each set of readings was made with the instrument at an angle of approximately 90° from the direction in which it faced during the previous set of readings. This was done to obtain a better average count for the material being tested. Also, all readings were made with no visible air gaps apparent between the surface of the material and the sources and detectors of the various gauges.

The materials were tested in the 24 inch split mold. They were built up in layers varying in thickness of from 3/4" to 1½ inches; the unit weight of the total sample being determined as each layer was placed. This procedure allowed for accurate determination of bulk unit weight. It was difficult to obtain unit weight using the sand replacement method on the gravel material and coarse sand when they were in a dry condition.

After the total layer height was equal to or greater than the depth of penetration for the instrument being tested, a count reading was obtained on each of the succeeding layers. This resulted in testing of from one to four layers depending on the instrument and type of material under study.

A standard count was taken both before and after testing each layer. Relative counts were used during all of this testing.

Variable density was obtained by varying the compactive effort and moisture content. Water was added to the mixture prior to each test run and the sample was then covered to prevent it from air drying over night. Each test was usually performed after the material soaked over night. Moisture determinations were made only on the top layer. Samples were taken from the mixture immediately after the testing was completed.

Densities of the various mixtures were determined using the sand replacement method whenever the existing conditions made this possible. These tests were obtained in addition to the bulk unit weight determined by weighing the entire sample.

RESULTS

Initial Testing

The initial testing program was conducted using only the Nuclear-Chicago instrument and consisted of two phases:

- (a) The testing of heavy liquids to determine their suitability for use as standards to check the constancy of the nuclear density gauges over an extended period of time. Concurrent with this investigation some of the factors which influence the nuclear count of the density gauge were examined.
- (b) The four soils described earlier were investigated with both the density and moisture gauges to determine the effect of soil type on the nuclear count number and to establish calibration curves.

Comparison of Liquid and Solid Standards

Since the problem exists of establishing suitable standards to check the nuclear density gauge for reproducibility at time of test, and for long term stability, it was considered that heavy liquids can be used to meet these requirements. Although liquids do not have the same atomic structures as the materials encountered in practice, the reproducibility and stability of the instrument must be independent of the material tested. Solid matter with a variety of atomic structures are present in aggregate systems which are encountered in practice. Liquid and air in these aggregate systems also have their particular structures. Therefore, the response of a material to the nuclear gauge must be dependent on material type. To check the reproducibility of the instrument, ideally a very uniform material should be used. On the strength of this argument a test program was initiated to determine the nuclear count response to heavy liquids with a range of unit weights to cover the range experienced in practice for typical soils.

It is first necessary, in the evaluation of the nuclear density gauge, to determine the volume of influence over which it will operate. For liquids this becomes a relatively easy matter since increase in depth and lateral extension of the liquid volume is accomplished without affecting the continuity of each layer or diameter of the liquid used. The uniformity of the liquid is also assured if conditions of testing are kept constant; unit weight can also be determined precisely.

Test Data on Heavy Liquids

Since the minimum volume of liquid required to give constant readings such that the container walls and air would not affect the results was not known, the lightest liquid, carbon tetrachloride with a unit weight

of 99.6 pounds per cubic foot, was tested first. A sufficient quantity of tetrabromomethane was obtained to provide the minimum volume required for 161.7 pounds per cubic foot after dilution with carbon tetrachloride. The other unit weights were obtained with further dilution.

Because the liquid in mixture form is a combination of carbon tetrachloride and the tetrabromomethane, the possibility of unequal evaporation can affect the unit weight of the liquid, but as this is very slight and can be prevented by suitable airtight storage containers, the problem is not a serious one. The principal advantage is that the liquid can be brought to the same unit weight at any reasonable temperature, thus ensuring absolute control over the standard. Difficulty over control of the uniformity of the unit weight during casting of concrete block standards, or variations occurring in their properties due to atmospheric changes in both concrete and stone blocks, reduce their reliability as standards, especially on a long term basis.

Data were obtained of nuclear counts at various liquid depths ranging from one inch deep to 8 inches deep for the heaviest liquid tested. This type of testing was made for each container until the size of the container at each depth appeared to have no effect on the readings. The variation of counts with increasing diameter for the lightest liquid is illustrated in Figure 3.

The variation of counts per minute with depth of carbon tetrachloride is illustrated in Figure 4. For this liquid the minimum depth of liquid for which no significant change in reading took place was about 6 inches.

It was found that for the heaviest tetrabromomethane-carbon tetrachloride mixture the minimum diameter of container to minimize edge

effects was 18 inches. The minimum depth of liquid for no significant count variation in the 18 inch container was about 3 inches. It was concluded on the basis of the above data, that testing of mixtures with unit weights ranging from 120.7 to 140.4 pounds per cubic foot requires containers at least 20 inches in diameter.

Results for the liquids tested at four unit weights in the 20 inch diameter container are presented in graphical form in Figure 5. Figure 6 illustrates the curve relating nuclear count per minute and unit weight of liquids.

Soils

The sand-soil mixture was compacted with the pneumatic compactor at different moisture contents in the 24 inch steel split mold. Each sample was compacted in 1.5 inch layers, with as near as possible equal effort per layer. The surface was carefully trimmed level so that good contact between the soil and gauge was obtained.

Measuring the unit weights and moisture of each mold, first by the nuclear gauges, then with the sand cone method, and finally by cutting away soil and covering it with paraffin wax presented little difficulty in the sand-soil mixture. The discrepancy of results between the sand cone and paraffin wax methods was disturbing, and it was therefore decided to determine the unit weights of the other materials by measuring bulk volume and weight. The unit weight test data plotted on Figure 7 for the sand-soil mixture was that obtained by the sand cone replacement method. The unit weights for the other three materials obtained in Figure 7 were determined as described previously.

During placement of the dry materials care was taken to cause as little segregation as possible. For the saturated condition, water was

first placed in the container and the soil then added. The water level was maintained so that the entire soil sample remained saturated during the time of placement. The dune sand was not tested in a saturated condition because of settlement of the sand that occurred under the weight of the gauge. Compaction of the damp dune sand was obtained with the pneumatic compactor.

Unit Weight and Nuclear Count Test Data

The test data in Figure 7 tend to be linear with the lines being approximately parallel to each other. There is a wide difference between the count readings of each soil type for the same unit weights. The best fitting curve through the points for each type of soil was computed by the least squares method using a linear distribution. The dashed line in Figure 7 is the manufacturer's calibration curve.

Moisture Test Data

Data for checking the calibration of the nuclear moisture gauge were obtained at the same time as data were obtained for the nuclear density gauge. The usual method of presenting moisture data for a nuclear gauge is to plot the weight of water, in pounds per cubic foot, against the average nuclear count. The curve for these data is plotted in Figure 8.

The least squares line in Figure 8 was calculated from data of 12 tests. The coefficient of linear correlation was 0.9955, indicating a high degree of correlation on the assumption that the moisture data in the range tested were linear. The dashed line in Figure 8 is a plot of the manufacturer's calibration curve for the moisture gauge.

Determination of High Voltage Plateau Curve

The high voltage plateau for the Nuclear-Chicago instrument was determined during the initial testing. The high voltage plateau curve is the plot of voltage energizing the detector stages of the density and moisture gauges versus the number of gamma ray or neutron back scatter counts per minute. It is obtained by setting the high voltage regulator at intervals starting from the lowest value for which the gauge will record counts to a sufficiently high level to detect the range within which the relationship will be linear. This linear region is termed the "plateau"; a suitable choice of operating voltage is somewhere in the center of this plateau.

Figure 10 is a plot of two such plateau curves determined during the test series described in the text.

Revised Testing

The revised testing program consisted of testing of the three different instruments (Viates, Nuclear-Chicago and Troxler) on the three soils described previously and using techniques described under the heading "Procedures". Some of the testing was performed using all three instruments on one test sample concurrently but most of the tests were run using just one instrument during each testing cycle. The results of this testing are presented in the form of calibration curves for each individual instrument. It should be noted that all calibration curves presented in subsequent graphs were determined using the least squares fit method of plotting straight lines.

Viatec

A total of nineteen density tests and eighteen moisture tests were run on the three soils using the Viatec Hydro-Densimeter. These soils were the sand-soil mixture, coarse sand and sandy gravel previously described.

Complete depth of penetration for both density and moisture readings have been determined for this instrument and are shown on Figures 11 and 12. These data were obtained from the curves shown in Figures 13 and 14.

Eleven sand cone densities were taken and correlated with the nuclear counts to give calibration curves based on the sand cone measurements of density. A curve of sand cone density versus an average of the relative counts obtained on several layers is plotted on Figure 15. Also, a curve of sand cone density versus the relative count obtained on the top layer alone is shown on Figure 16.

Using the bulk densities as measured by previously described methods, calibration curves of relative count versus bulk density were determined. Figure 17 shows the curve of average bulk density versus the average relative count of the layers tested whereas Figure 18 illustrates the average bulk density versus the relative count of the top layer tested only.

Figure 19 is a composite set of curves of the previously mentioned relative count versus density curves. It can be seen that these curves fall almost on top of each other with their slopes being approximately equal. Also plotted on this figure is the Manufacturer's Curve. It is seen to be parallel to the other four lines but it is offset from these laboratory curves. It is believed that if the manufacturer had used the same standards as used in this study, their line would be the same as

those reported herein. This consequently leads to the conclusion that the manufacturer's stated standard on their calibration curve was possibly in error.

The moisture content determinations made at the end of each density test were converted into pounds of water per cubic foot of material and correlated with the nuclear counts obtained using the Viatec moisture gauge. A curve of relative count versus pounds of water per cubic foot of material was plotted as shown in Figure 20. This figure shows a composite curve of the moisture contents versus relative count for all of the three soils tested during this phase.

A high voltage plateau curve was also determined for this instrument during this stage of testing. This was accomplished in a similar manner as to the method described previously for obtaining the high voltage plateau curve for the Nuclear of Chicago instrument. This curve is shown on Figure 21. Also shown on this figure are relative count on a standard concrete block versus high voltage curves. These were determined on two different dates and are seen to vary somewhat.

Nuclear-Chicago

Further testing of the Nuclear-Chicago instrument was also accomplished during the secondary testing phase. This testing was done using the test materials previously described and an attempt was made to correlate these data with data observed during the initial testing period.

Calibration curves of relative count versus density for each of the three soils are shown in Figure 23. These lines are seen to be approximately parallel to each other and an equation of the calibration curve is indicated for the sandy gravel and the coarse sand materials.

In an attempt to obtain a more level surface on which to place the instrument when testing the sand-soil mixture, a leveling course of sand was placed on the surface of each test layer. Curves of relative count versus density for both cases, i.e., with and without the leveling course, are shown on Figure 24.

Figures 25 and 26 show calibration curves for the coarse sand material for both the initial and revised testing phases. The initial phase was accomplished during April 1962 whereas the revised testing was done during the month of November 1962.

Figure 25 shows a set of curves for counts per minute versus density whereas Figure 26 shows the relationship of relative count versus density. It can be seen that for both methods of comparison, the curves are parallel to each other but offset from each other by approximately the same relative amount.

Troxler

Due to minor failures of the Troxler instrument, insufficient data has been collected to present a calibration curve for this instrument at this time.

DISCUSSION OF RESULTS

Initial Testing Phase

Heavy Liquid as a Standard

The curves plotted in Figure 5 indicate that beyond a certain critical depth the response of the nuclear gauge gamma ray back scatter is constant. This suggests that due to the homogeneity of the liquid, the gamma ray activity was dependent only on the instrument itself. This fact then provides evidence that: (a) the instrument is consistent in its response to a homogenous system, and (b) if a liquid is used as a standard, the instrument's reproducibility can be ascertained with a high degree of

This consistency of the counts per minute with increasing depth is shown in Figure 5. Analysis of the data shows that for the last four count readings of each of the four liquids tested, the greatest deviation from the mean is 88 counts per minute. However only one out of sixteen counts considered had this high deviation from the mean, the remaining fifteen readings being less than 42 counts per minute from the mean. This deviation of 42 counts per minute from the mean represents a variation of about half a pound per cubic foot of density in the higher unit weights and less for the lower unit weight range.

The purpose of a standard is to permit checking the instrument at regular intervals to ensure that its calibration characteristics remain constant. From the data presented it would seem reasonable to state that provided the liquid volume is large enough to prevent gamma rays from escaping outside the liquid, the liquid will act as a high quality standard to check the density gauge calibration. It can therefore also be used to determine the count ratio of test count readings.

From the data plotted in Figure 4, for the 99.6 pcf liquid a diameter of 20 inches appears to be the minimum diameter of container which must be used. Also, from the data it can be ascertained that an 18 inch diameter container should be the minimum diameter for the 161.7 pcf liquid, the heaviest one tested. It would therefore appear reasonable to conclude, that in general a container greater than 18 inches in diameter should be employed.

The dashed curve in Figure 5 shows the critical minimum depths at which the nuclear counts are constant. This critical minimum depth curve is typical of the type of information that is required to determine the depth to which the nuclear density gauge measures. Similar data for soils

with the same gauge should indicate whether the determination of the critical depth by means of liquids can be used in practice. Use of liquids greatly simplifies the problem of determining the minimum volume of soil measured by the nuclear gauge, particularly if the instrument is to be used for determining the unit weight of thin layers of compacted soil, bituminous or concrete pavements. Owing to the difficulty in controlling the unit weights of each layer it becomes somewhat difficult to determine the same information for solid materials or soils.

If liquids can be successfully used to determine the depth of influence measured by the nuclear density gauge, and since the liquids give consistent response to the gauge, they would then be more reliable standards than solids. However, since they are toxic, are difficult to handle and give off noxious fumes, the writers prefer solid standards at the present time.

Calibration for Soils Studied

The purpose of testing actual soils with the nuclear density and moisture gauge is to permit determination of in-situ moisture and density in relatively short periods of time. It is however pertinent to appreciate that because of different philosophies of approach to testing in the field and in the laboratory, the validity of an instrument's calibration in the laboratory is generally questioned by field personnel, and likewise the restrictive considerations of the laboratory approach will in general reject field calibration.

The literature abounds with data where excellent laboratory curves are shown for a particular type of instrument, and widely scattered data recorded for a similar instrument when calibrated in the field. In a recent symposium published by the American Society for Testing and Materials (3) there are expressed widely differing view-points on the

calibration of nuclear gauges. Some of the authors of this symposium believe that a nuclear gauge must be calibrated in the field, and others that calibration should be carried out under controlled conditions in a laboratory. Opinion also differs as to whether a moisture gauge should be calibrated against a chemical equivalent standard or by actual oven dried soil moisture methods. The report from the Engineering Experiment Station of the Ohio State University (4) reports on calibration of similar gauges by the university staff and the Department of Highways. From the results obtained by the two authorities, the calibration curve obtained under laboratory conditions at the university does not reflect the scatter of data which is typical of the field calibrated instrument. It would appear therefore that results of calibration tests bear some relation to the method of testing.

Usually in the field, nuclear counts are related to measurements made by one of the standard conventional methods of measuring in-place density, (i.e. sand cone). These seldom, under field conditions, produce the true unit weight of a material. The reasons for this are varied and are principally concerned with the measurement of the volume of a known weight of excavated material. Redus (5) determined the accuracy of some of the methods of measurement of soil unit weight under laboratory conditions, and states that sand density cylinders will on the average produce a degree of accuracy of ± 2.5 per cent from the mean.

Carey and associates (1) report on their investigations relative to evaluation of testing equipment as follows:

"The following shows the means and standard deviations for the 20 individual measurements of wet density obtained in the study:

	Mean, lb per cu.ft.	Standard Deviation, lb per cu ft
Nuclear gauge	147.7	0.7
Balloon Volumeter	150.3	4.8
Sand cone device	150.5	4.9

There was in this experiment, an approximate 2.7 lb per cu ft difference in mean density determined by the nuclear method as compared with the conventional methods. There was also an appreciable difference in standard deviation. Since the true mean and standard deviation of density in the compacted material was unknown, there was no way of determining which of the three methods came closest to the truth.-----Because extreme care was taken in the preparation of the compacted base material for this experiment, the authors doubt that the large variability indicated by the balloon and sand cone existed. The low variability indicated by the nuclear device appeared to be nearer the truth."

Data as presented and reported by J. R. Sallberg in his discussion to Radus' article (5) represents a summary of the average values of a number of tests obtained from a study carried out at the Division of Physical Research of the Bureau of Public Roads. A difference of about 8 pcf between the standard sand cone and undisturbed method (which correlates with the oil method), indicates the possibility of error if the sand cone is used as a method of control in the field. During the present investigation differences ranging between 5.5 and 6.9 pcf were recorded. These differences pose an unanswered question relative to which standard (sand cone or undisturbed sample) should be used for calibration in both the laboratory and field.

It becomes necessary, therefore, to re-examine methods of measuring density because the possibility exists that the nuclear gauge may yield more accurate results than the conventional methods. During the present investigation, densities were determined from bulk volume measurements for the major portion of the test program. It is believed that measuring the bulk volume and weight yielded more accurate results than did the sand cone method.

Accuracy of the Nuclear Density Gauge

Assuming the density gauge response was statistically accurate for the standard against which it was checked before every test, the data presented in Figure 7 indicate different linear correlations for each of the materials. The coefficients of linear correlation are given in Table 2. These indicate a high degree of correlation between counts per minute obtained with the density gauge and the unit weight of the soils.

A standard with a known unit weight was not used to check the instrument against. The checks performed were adjustments to ensure that the instruments reproduced before each test the correct readings on the standards provided by the manufacturer. The voltage settings were adjusted to obtain the correct standard readings.

A concrete block made of standard Ottawa sand and cement was fabricated to be used as a standard. However, difficulties occurring during the casting and curing raised several questions relative to the suitability of the block for use as a standard. The counts obtained on this block are given in Table 3. The counts per minute measured on water in a 24 inch diameter container is also given in Table 3. This latter value is lower than that quoted for water by the manufacturer. This indicates a change in the calibration of the instrument as determined by the manufacturer.

It is desirable that additional tests be made to determine whether the two procedures (manufacturer's standard and solid standard) for checking the instrument show any significant differences. Data obtained in this study have indicated the possibility of using a liquid standard because of its homogenous structure.

The extent to which air in the voids affected the readings is not known. Special provision, however, was made to ensure proper seating of the gauges on the surface so that no air gap was present under the gauge, especially under the detector tubes. Addition of fine sand to the surface of the gravel and coarse sand eliminated unusually high gauge readings due to air.

The data suggested that a single line cannot be used to represent an overall calibration curve for the materials tested. Data by other investigators also indicate that different materials plot on separate lines (3) (4). The dashed line in Figure 7 shows the single calibration curve obtained by the manufacturer on specially prepared concrete blocks. This point, however, must be checked further for the instrument in question. There is a need to obtain basic data to determine the reasons for the apparent differences in the calibration curves.

Effect of Moisture Content on Density versus Counts per Minute Readings

The soils in this study were compacted when dry, saturated and at intermediate moisture contents.

Carlton (6) has suggested that for a particular nuclear density instrument, the unit weight versus counts per minute curves may plot in a series of straight lines at constant moisture content for all normal types of soil. Data obtained during the investigation and plotted in Figure 9 indicate such a possible trend. However insufficient data were obtained to confirm this hypothesis clearly.

Figure 9 indicates for the four soils tested, that at a particular unit weight, regardless of the soil type, as the moisture content increases,

there is an increase in the nuclear counts per minute. Further testing is necessary to confirm the significance of this trend and to determine whether it holds true generally for all types of soil over a wide range of unit weights.

If the above proves to be the case, practical calibration curves will be obtained for the nuclear density gauge which are independent of soil type and are dependent only on unit weight and moisture content.

Factors Affecting the Stability of the Density Gauge

Table 4 indicates the spread of the five readings taken for each test, calculated from the statistical reliable error permitted based on the Poisson distribution. Nearly all the readings used for the average counts per minute for each test were within the upper and lower limits of the reliable error (90% confidence level). The gauge appears to have remained fairly stable during the period of testing as is shown on the high voltage plateau curve plotted in Figure 10. This figure is a plot of the voltage settings against the counts per minute readings for the density gauge - scaler system. Two sets of readings were taken. One was taken at the commencement of the test series, and the other soon after testing of the dune sand was completed. Since little change occurred during this period it seems logical to conclude that the instrument did not show any serious variation in response to the environment.

The nuclear density gauge was also checked in a cold room to determine if temperature had any effect on the gauge. The data obtained for this indicate that in the manufacturer's standard, the gauge lost about 440 counts per minute when cooled for 5 hours from a temperature of 83°F

to 42°F. The 440 counts represent about 1 percent of the standard count of 43215 counts per minute. This is only about 0.2 percent more than the reliable error which can be expected at this count. During the period of testing for the data plotted in Figure 7, the temperature was in the mid-seventies, so that this factor is not considered to be a contributing factor in the difference of position of the plots of the four soils.

Moisture Calibration

The data plotted in Figure 8 indicate a good correlation between oven dry moisture content, (105°C) against nuclear counts per minute within the range of moisture contents measured. The manufacturer's standard provided for the gauge is obviously well calibrated to conditions which represent oven drying. Therefore if the high voltage setting is adjusted to produce an average count per minute on the standard close to that specified, the calibration line shown in Figure 8 should provide a good estimate of the moisture content for tests on soils similar to those tested.

Within the moisture range tested, there appeared to be little effect on the moisture calibration due to the type of soil tested. The gauge must however be checked against soils containing higher percentages and different types of clay minerals. For all four different soils the limits of variation of the five readings taken for each moisture content were well within the reliable error limits of the instrument.

Testing Using Revised Techniques

Viatec Calibration Determinations

Because of the scaler design, adjustment of the high voltage to yield identical standards for every test was not feasible. Therefore, use

of the count ratio method was decided upon, with the standard operating voltage remaining constant. Variance of standards was appreciable with ranges of density standards of from 20,250 counts per minute to 18,500 counts per minute. This is shown on Figure 22 for both density and moisture gauges. All standards were taken with the self-standard case located on the concrete floor of the testing area.

Also, at the same time as the voltage plateau curve data was being taken, readings were taken on a concrete block which was placed on a wooden platform just above the concrete floor. These data are plotted on Figure 21 and show the variance in the relative count as compared to the voltage for two different dates. Although the two curves are displaced from each other somewhat they do show that the relative count was fairly stable at high voltages above approximately 880 volts on the date on which the readings were made. It was assumed that the depth of penetration for the Viatic density gauge did not exceed the thickness of the test concrete block.

Depth of penetration curves for both density and moisture (See Figures 11 & 12) were constructed by taking counts on successively built up layers of soil. For density penetration, a close correlation between the depth curve furnished by the manufacturer and the laboratory constructed curve was found to exist. Depths of penetration as determined in the laboratory ranged from approximately 8 inches at 100 pounds per cubic foot to 4 inches at 150 pounds per cubic foot as shown on Figure 11. It should be emphasized that these are approximate values. Since no moisture penetration curve was available from the manufacturer, it was impossible to make any comparisons using the laboratory constructed curve. Depth ranges for

moisture as shown on Figure 12 range from 12 inches at 2 pounds of water per cubic foot to 5 inches at 20 pounds of water per cubic foot.

By utilizing densities determined by the sand cone method and by direct measurements, along with a relative count reading for the last layer tested and an average of the relative count for the several layers tested, it was possible to establish the four calibration curves as shown on Figures 15, 16, 17 & 18 relating mass density to count ratio. Lines of regression were calculated for each curve and their equations are shown on the corresponding figure. Although a statistical analysis was not available it is evident from Figure 19 that a high degree of correlation existed among all four curves.

The calculated density curves when plotted on a count ratio basis and compared to the manufacturer's curve were qualitatively higher, but parallel, to the manufacturer's curve. However, when all four density curves were transformed to a pure counts per minute basis and compared to a similar manufacturer's curve, they were found to be highly similar. Consequently, it was concluded that the standard recommended by the manufacturer was in error and a new standard was established. Also, the fact that the pure counts per minute curves for the manufacturer's calibration and the laboratory calibration were highly similar gave evidence to the conclusion that testing completed thus far was free from all outside influence from the other instruments under investigation.

Since it was shown that the type of compactive effort (poured loose or pneumatically tamped) affected the calibration curves, only tamped efforts were utilized. This was done to minimize the error due to settlement of the soil under the weight of the instrument itself if placed on a loosely placed soil. Since only tamped efforts were used it was necessary to work within a restricted range of densities thereby limiting the amount of data that could be obtained.

As pertaining to the moisture calibration for this instrument; the regression curve is shown on Figure 20 along with its equation and this curve indicates a high degree of correlation.

Further Viatec Investigation

Several weeks after the conclusion of the testing on the Viatec instrument, a visit to the campus was made by several personnel of Viatec and the data thus far obtained was discussed. Several modifications of testing procedures were discussed, one being the use of an air gap under the self-standard case to achieve constant standard readings. It was noted by the Viatec representatives that it has been found that inconsistencies in standard readings will be obtained if the self-standard case is placed on any surface in the absence of an air gap between it and the foreign surface. This is due to the fact that penetration during self-standard tests is greater than the thickness of the self-standard case; thus substrate effect of the surface on which the gauge rests will bring about various discrepancies.

It was also mentioned that it has been found that the voltage applied by the internal battery for scaler operations is somewhat more critical than at first realized in the initial design of the gauge, and that the possibility of battery voltage affecting intensity readings exists.

Therefore, it is recommended that data be obtained to show the definite limits of battery voltage as being critical in test readings. Also, the introduction of an air gap while taking standards can be used to demonstrate the effectiveness in determining standards which will remain within statistical errors of a constant value standard.

Difficulty was experienced in the Viatic instrument relative to obtaining consistent standard readings (see Figure 22). The instrument was returned to the manufacturer and it was found to have a faulty linkage. Therefore some doubt exists as to the validity of some of the relative count data. Therefore, the possibility exists that data shown in Figures 15 through 19 should be re-plotted using absolute counts rather than relative counts.

Nuclear-Chicago

During the later testing of the Nuclear-Chicago instrument the three density calibration curves shown on Figure 23 were obtained. This figure shows that a definite density calibration curve exists for each individual soil and that the three curves are approximately parallel to each other. When compared to the curves obtained for these three soils during the initial testing phase, it can be seen that they are all approximately parallel to each other but that the set of curves obtained during the secondary testing period are offset from those obtained during the initial phase.

Figures 25 and 26 illustrate this shift for the coarse sand. The shift is noted to be approximately the same whether the relative count or counts per minute is plotted against density. It should be noted that the standard reading was different during the two testing periods. This difference was approximately 1000 counts per minute. However, as can be seen from Figure 27, for a change in counts per minute of 1000 a change of only about .02 in

relative count is observed and therefore this should not affect the results enough to cause the shift observed.

A difference in standard counts was also encountered for the testing of each soil during the secondary phase. The time period involved was approximately one month but as was just shown, a change in standard reading of about 1000 counts per minute will not affect the relative count to any great extent and it is therefore concluded that the change in standard reading with time is not the cause of the three different calibration curves shown on Figure 23.

Both testing phases were performed in the same physical surroundings and using approximately the same testing procedures. The only significant differences were that the operators were different for each testing phase and that other instruments were present during the secondary phase and not during the initial phase. It has been shown previously that the presence of the other sources did not affect the readings as they were kept behind a concrete wall during testing.

On Figure 28 is plotted a curve of relative count versus density for the dune sand obtained during the initial testing phase by operator number one. Also plotted on this figure is a point obtained on the same material under exactly the same conditions except by operator number two. This point is found to coincide with one of the initial points thereby eliminating the operator as the reason for the shift of curves from one testing period to the other.

It is thereby suggested that the reason for the shift lies in the instrument itself but no exact explanation may be offered at this time. The cause of this shift is under investigation and it is hoped that the source causing this discrepancy may be located.

As shown on Figure 24, it can be seen that by using a fine sand leveling course, a more well defined calibration curve was obtained for the sand-soil mixture tested. This is probably due to the fact that the sand filler helps to minimize the air gaps under the density gauge during testing. Due to the geometric design of the Nuclear-Chicago instrument, the possibility of more air gaps existing than for the other instruments is prevalent and therefore the use of the filler material helped to minimize this.

Troxler

Since the initial receipt of the Troxler instrument, relatively few data points have been established due to instrument difficulties. Consequently, at this point in the testing program, no results based on an evaluation of the instrument can be given.

Supplementary Data

During the revised testing phase, a comparison was made between density as determined by the sand cone method and bulk-volume density. Plots of sand cone density versus calculated bulk-volume density are shown in Figures 29 and 30. Also, as mentioned under revised testing methods on page 11, an investigation to determine the background effects of additional instruments was made and the results of this research are shown in Figure 31.

SUMMARY

The following summarizes the findings relative to the behavior and quality of the gauges as tested on the materials described.

1. The results indicate that liquids can be used with a high degree of accuracy as a standard due to their homogenous characteristics and the fact that their densities can be determined accurately. However, due to the inconvenience of handling liquids and the noxious nature of their fumes, solid standards are preferred.
2. The depth of influence to which the density gauge measures can easily be checked by using liquids.
3. A limiting factor during calibration of a nuclear density gauge is the accurate physical determination of the actual unit weight of a soil. Uniformity of compaction is also troublesome.
4. A major factor affecting calibration is the variations in standard readings from test period to test period.
5. Each soil tested appears to have a definite linear counts per minute - unit weight relationship. The degree of correlation for each soil unit weight versus counts per minute or relative count depending on the testing phase was high for the instruments tested. However, the data were scattered making it impossible to draw a single calibration curve for all of the soils for either instrument. Degree of saturation appeared to influence the unit weight versus counts per minute or relative count for all soils tested.

6. Even though the counts vs. density curves were linear and approximately parallel, data obtained in this study indicated that they shift from time to time. This shift is no doubt due to changes in the instruments themselves. Also, some of the data suggest the lines may not be parallel throughout the entire density range.

The above, coupled with the fact that each soil has its own calibration curve, raises a question regarding the feasibility of attempting to establish calibration curves in the laboratory. Additional work should be done to clarify this point.

7. The manufacturers density calibration curves for all gauges have been different than those obtained during this study.

8. The moisture calibration curves for the moisture gauges tested are linear and yield a high degree of correlation. The quality of linearity and correlation for the soils tested was not affected by types of soils.

FUTURE WORK

Primary Work

The following fields of investigation are planned on being undertaken at Purdue during the coming year. These are considered necessary areas to be studied before a thorough evaluation of the nuclear system can be attempted.

1. Perform further tests to determine the reasons for obtaining different calibration curves for different soils, that is, investigate the effect of soil type, soil composition and grain size distribution on the counts per minute reading for each instrument. Tests on this are in progress.
2. Perform further tests to determine the extent moisture content influences the unit weight - nuclear counts per minute relationship.
3. Compile a complete set of laboratory calibration curves for both the density and moisture gauges for all three instruments.
4. The instruments will be taken into the field and calibration curves constructed from data taken under actual field conditions. This will be done during the summer of 1963.
5. A correlation will be attempted between the field and laboratory calibration curves.
6. Tests will be performed to ascertain the feasibility of measuring the thicknesses of asphaltic concrete and concrete pavements by means of the nuclear density gauges. Plans are being made to do this work in the very near future.

Secondary Research

The following fields of investigation are suggested as important areas to be investigated in order that a complete evaluation of the nuclear system can be accomplished. However, due to a lack of time, these phases are not planned to be undertaken during this present study of the nuclear instruments.

1. A thorough evaluation of the types of materials that can be used as standards to check the nuclear density gauge should be made.
2. Further study should be made of methods of physically measuring true soil density.

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TABLE 1

PHYSICAL DATA OF SOILS STUDIED

	Max. Std. AASHO Dry Density pcf	Optimum Moisture Content %	Plasticity Index	Specific Gravity
Sand-Soil Mix	121.4	11.6	16	2.67
Gravel	132.8	9.2	NP	2.65
Coarse sand	(113.7)	(14.5)	NP	2.71
Dune sand	105.3	10.0	NP	2.64

TABLE 2

REGRESSION LINE EQUATIONS AND COEFFICIENTS
OF LINEAR CORRELATION FOR SOILS TESTED

Soil Type	Equation*	Coefficient of Linear Correlation
Sand-Soil Mixture	$Y = 23069 - 98.444 X$	
Gravel	$Y = 19309 - 68.395 X$	- 0.9967
Coarse Sand	$Y = 18730 - 68.955 X$	- 0.9824
Dune Sand	$Y = 22588 - 88.338 X$	- 0.9990

Y = Average of five counts per minute

X = Unit weight of soil

*Least squares regression line, where X is the independent variable.

Standard Error of Estimate for Coarse Sand.

$S_{y.x} = 167$ counts per minute.

TABLE 3

TEST DATA FOR SOILS STUDIED

Test No.	Soil Type and Compaction	Wet Unit Weight pcf	Average Counts	Voltage Setting	Calibration Counts
<u>Sand-Soil Mixture</u>					
1	Pneumatic Compacted	117.3	11784	975	43071
2	Pneumatic Compacted	126.8	10145	975	43385
3	Pneumatic Compacted	138.0	9414	975	43153
4	Pneumatic Compacted	140.0	9535	985	43232
<u>Coarse Sand</u>					
5	Poured Damp	86.1	13938	1005	43116
6	Poured Dry	99.0	11887	990	43142
7	Poured Dry	99.5	11674	990	43108
8	Vibrated Dry	113.0	11079	990	42875
9	Vibrated Dry	113.5	10871	990	43125
10	Compacted Damp	118.3	10891	1005	43239
11	Poured Saturated	129.8	9724	995	43143
12	Vibrated Saturated	135.6	9228	995	43302

Table Continued

Test No.	Soil Type and Compaction	Wet Unit Weight pcf	Average Counts	Voltage Setting	Calibration Counts
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Gravel

13	Poured Dry	94.9	12775	995	43199
14	Vibrated Dry	109.3	11899	995	43199
15	Compacted Damp	127.5	10674	1000	43171
16	Vibrated Saturated	129.7	10332	995	43362
17	Poured Saturated	132.8	9600	995	43277

Dune Sand

18	Compacted Dry	85.3	15028	1000	43127
19	Compacted Damp	103.5	13486	1000	43277
20	Compacted Damp	114.4	12493	1000	43271
21	Compacted Damp	115.5	12425	1005	43140
22	Compacted Damp	119.5	11965	1000	43197
23	Water	62.4	18859	990	43125
24	Concrete Block	131.6	10887	1000	43275

TABLE 4

COMPARISON OF UPPER AND LOWER LIMITS OF
DENSITY GAUGE COUNTS AND RELIABLE ERROR LIMITS

Test No.		Average Count	Actual Lower and Upper Limits	Reliable Error Lower and Upper Limits
1	SSM	11784	11707 - 11879	11600 - 11968
2		10145	10077 - 10202	9998 - 10292
3		9414	9306 - 9544	9254 - 9574
4		9535	9345 - 9760	9374 - 9696
5	CS	13938	13769 - 14192	13744 - 14132
6		11887	11747 - 12127	11708 - 12066
7		11674	11470 - 11919	11495 - 11853
8		11079	10917 - 11238	10906 - 11252
9		10871	10697 - 11127	10699 - 11043
10		10891	10741 - 11011	10719 - 11063
11		9724	9625 - 9780	9562 - 9886
12		9228	9179 - 9254	9069 - 9387
13	GR	12775	12648 - 12918	12589 - 12961
14		11899	11828 - 12008	11719 - 12079
15		10674	10582 - 10784	10503 - 10845
16		10332	10240 - 10401	10164 - 10500
17		9600	9541 - 9646	9439 - 9761
18	DS	15028	14962 - 15242	14828 - 15028
19		13486	13344 - 13625	13295 - 13677
20		12493	12319 - 12643	12302 - 12684
21		12425	12285 - 12554	12235 - 12615
22		11965	11941 - 11993	11784 - 12145
23	Water	18859	18694 - 19071	18633 - 19185
24	Con- crete block	10887	10780 - 11020	10715 - 11059

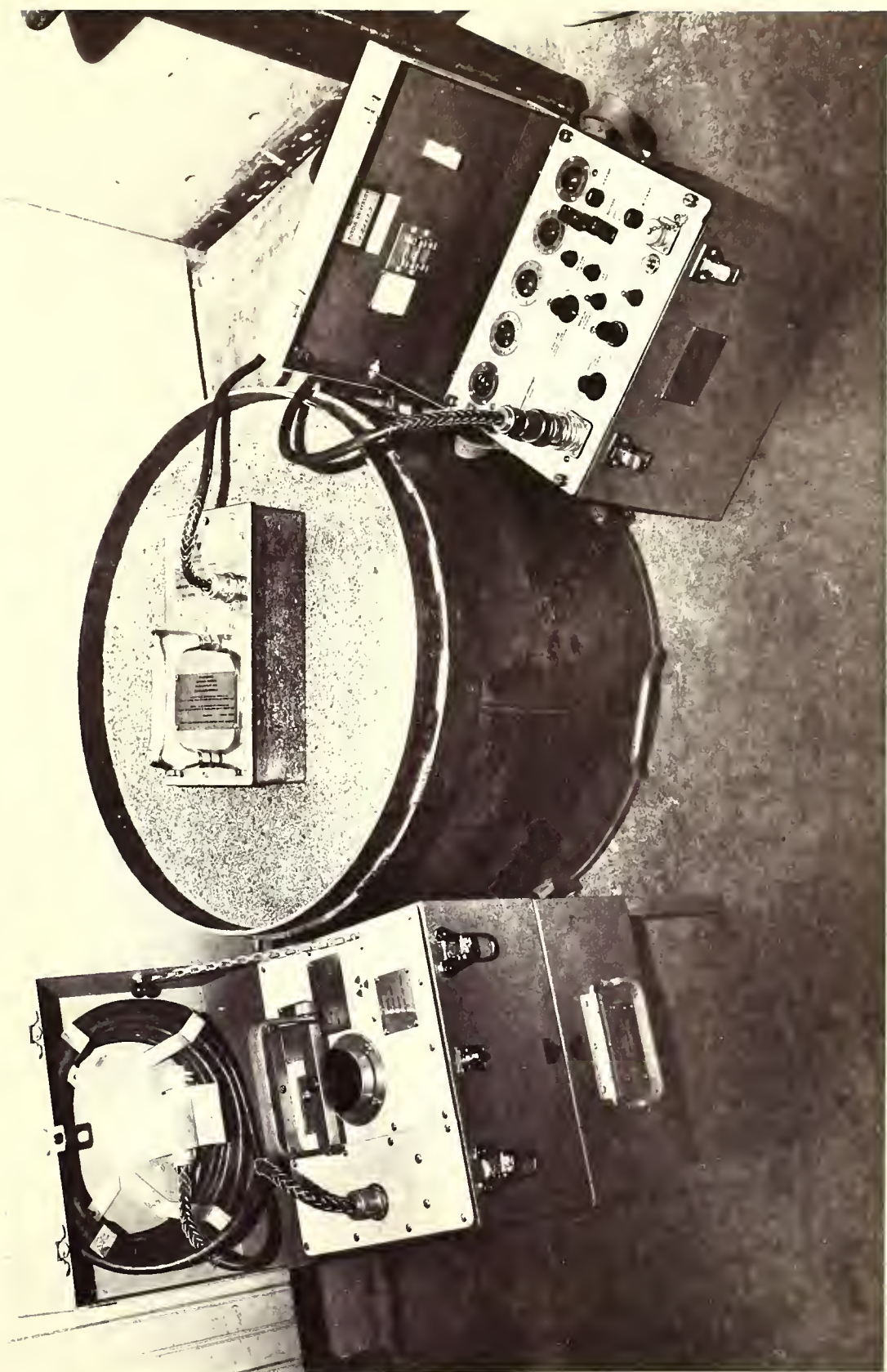


PLATE I

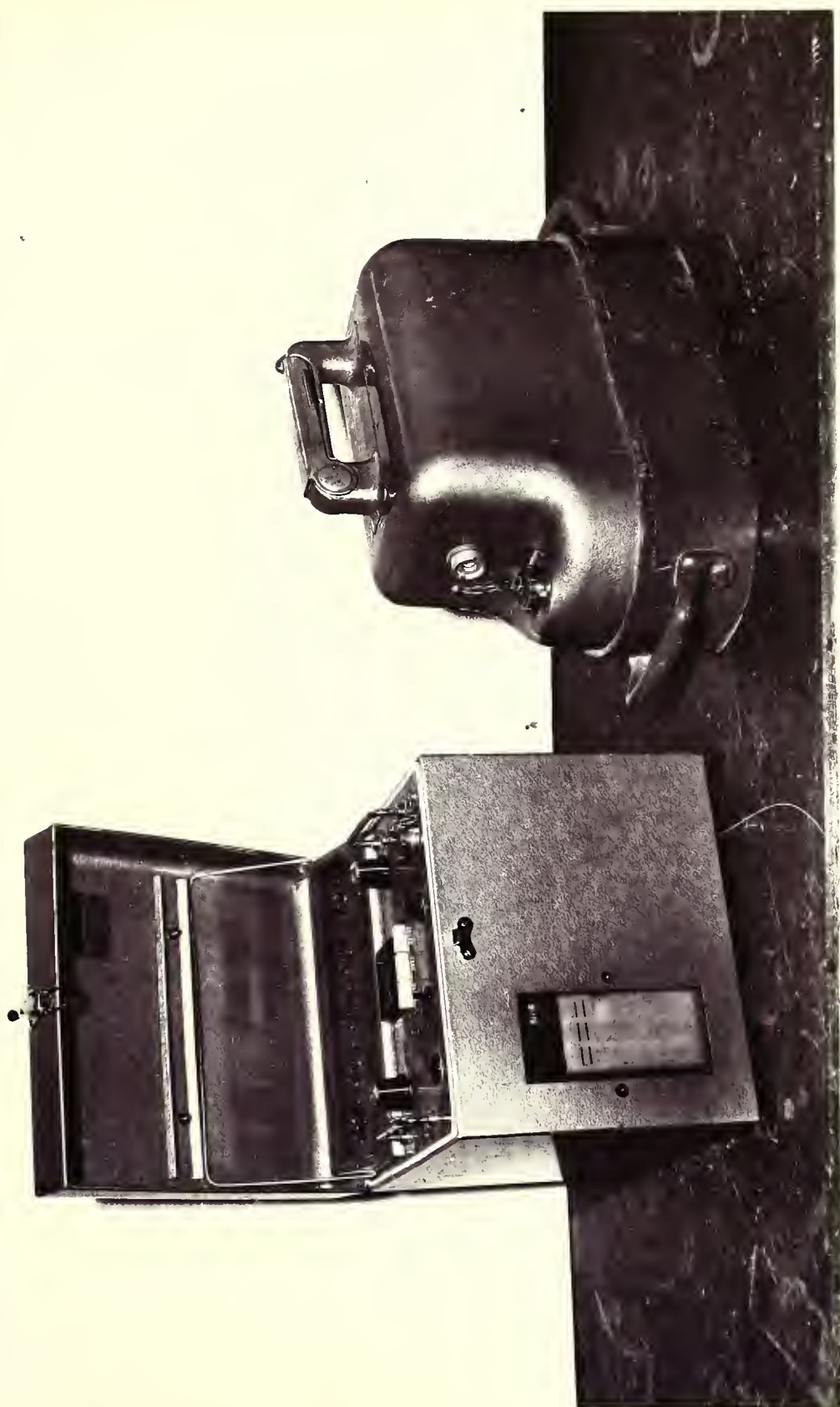


PLATE 2

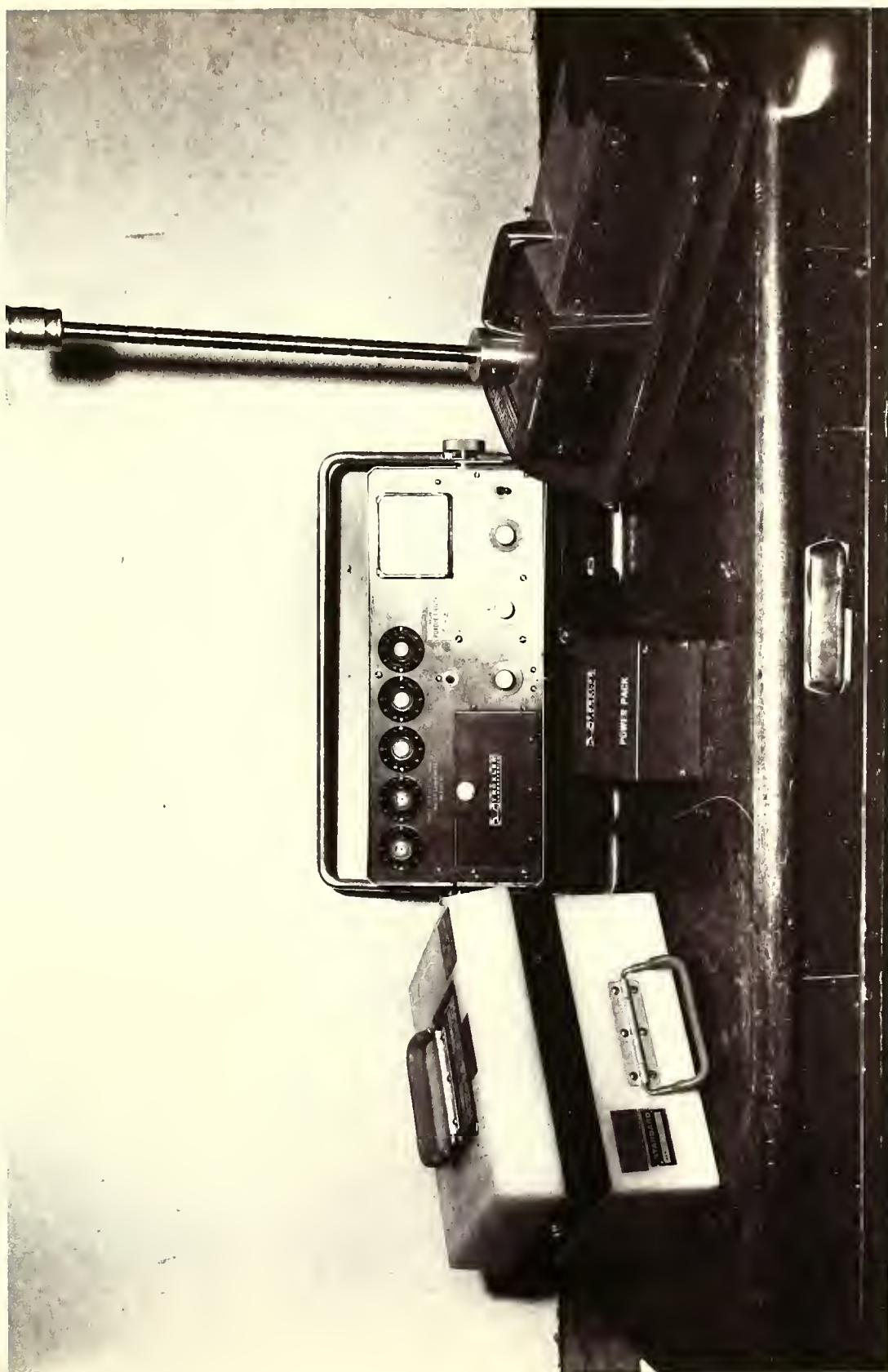


PLATE 3

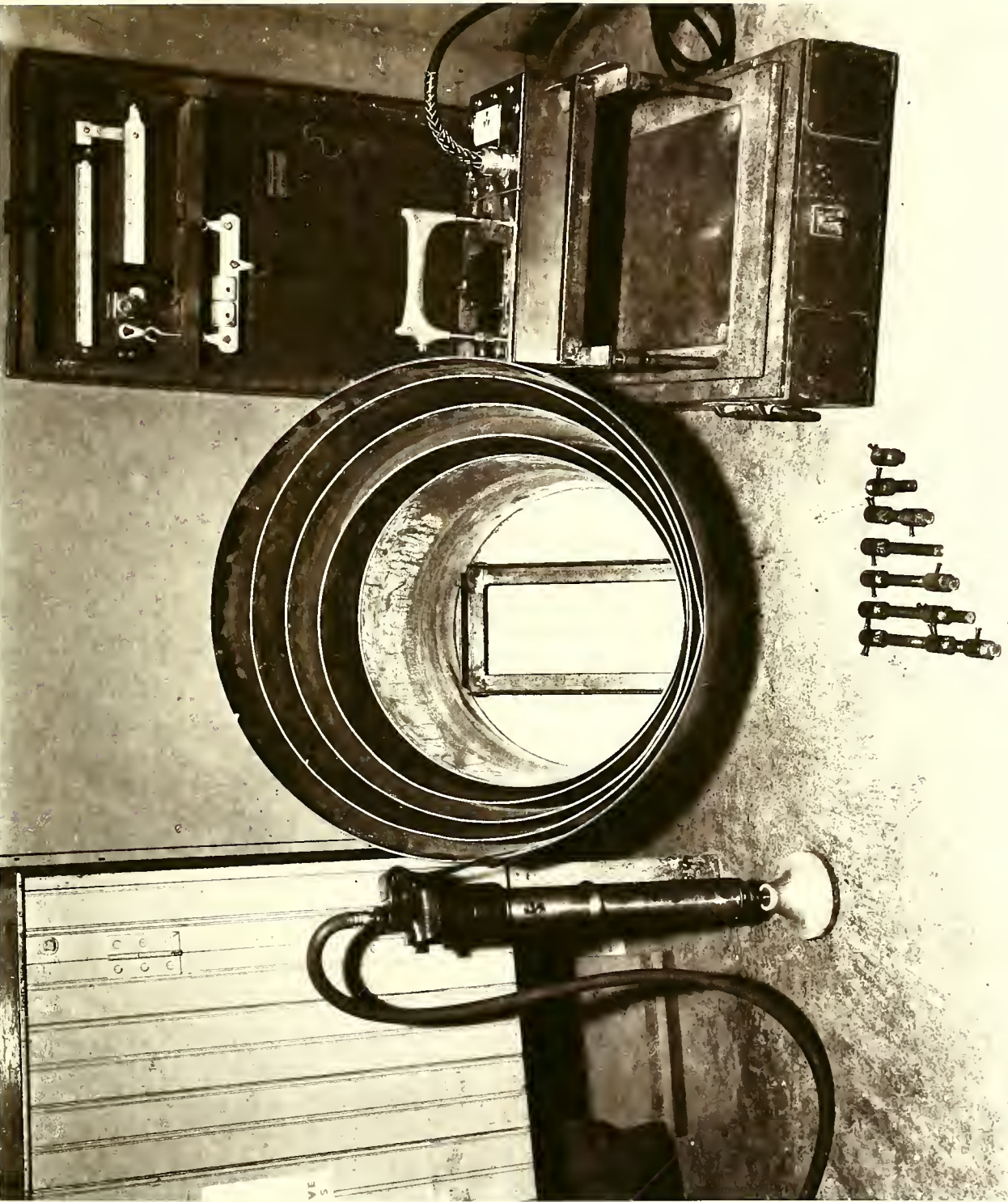


PLATE 4

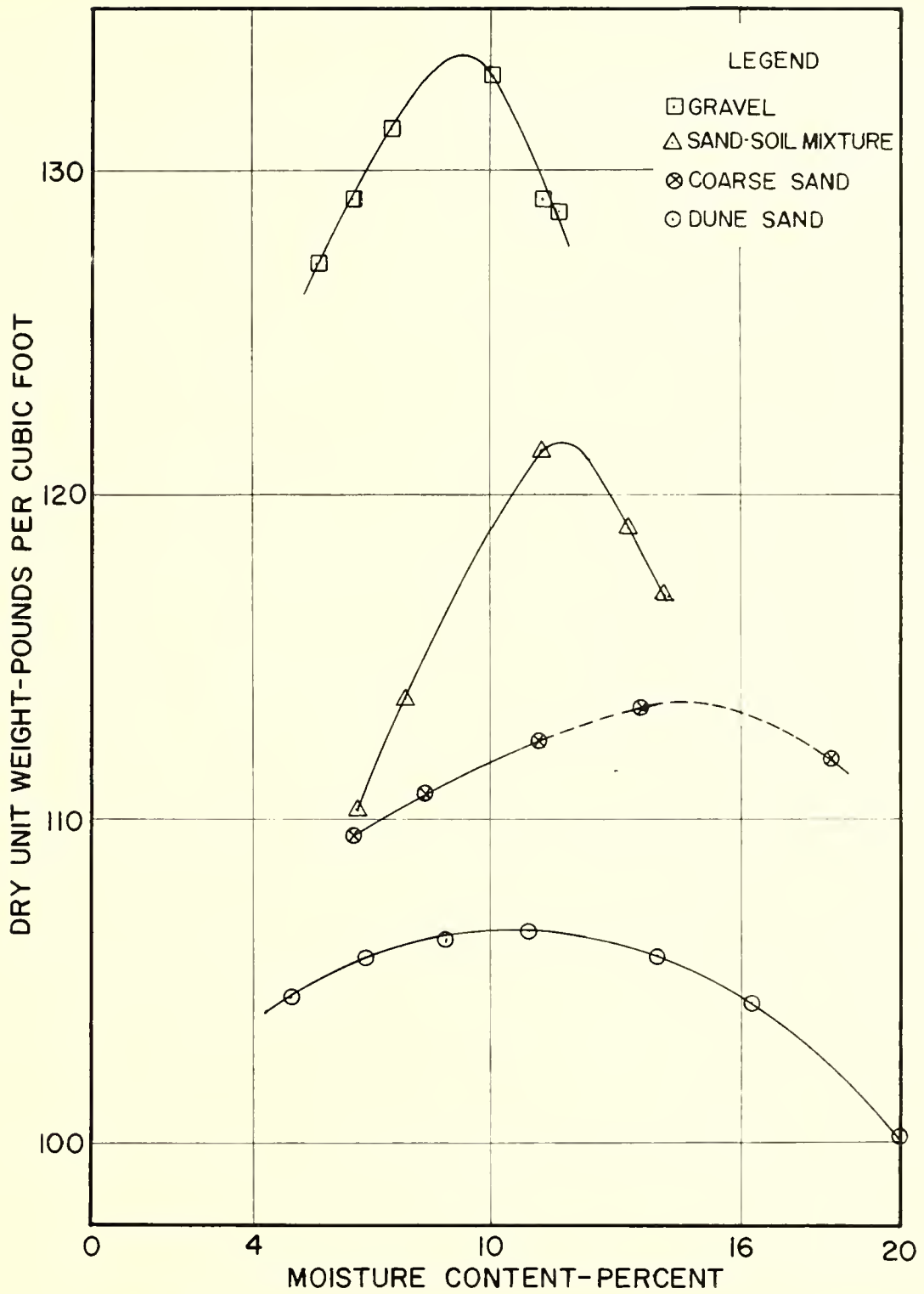


FIG. 2 STANDARD AASHTO COMPACTION CURVES
FOR SOILS TESTED

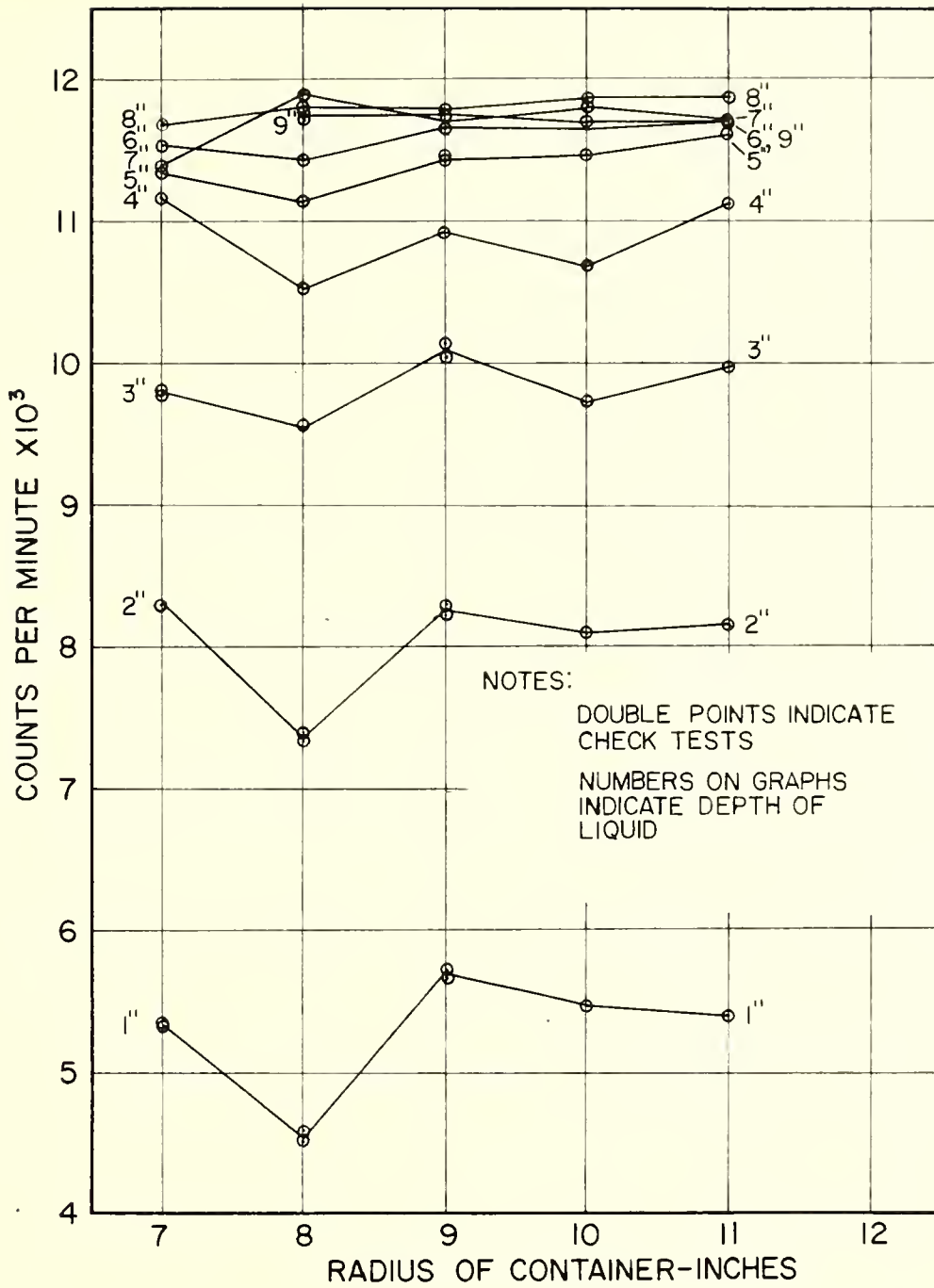


FIG. 3 COUNTS PER MINUTE VERSUS RADIUS OF CONTAINER FOR VARIOUS DEPTHS OF LIQUID (99.6 PCF) NUCLEAR CHICAGO

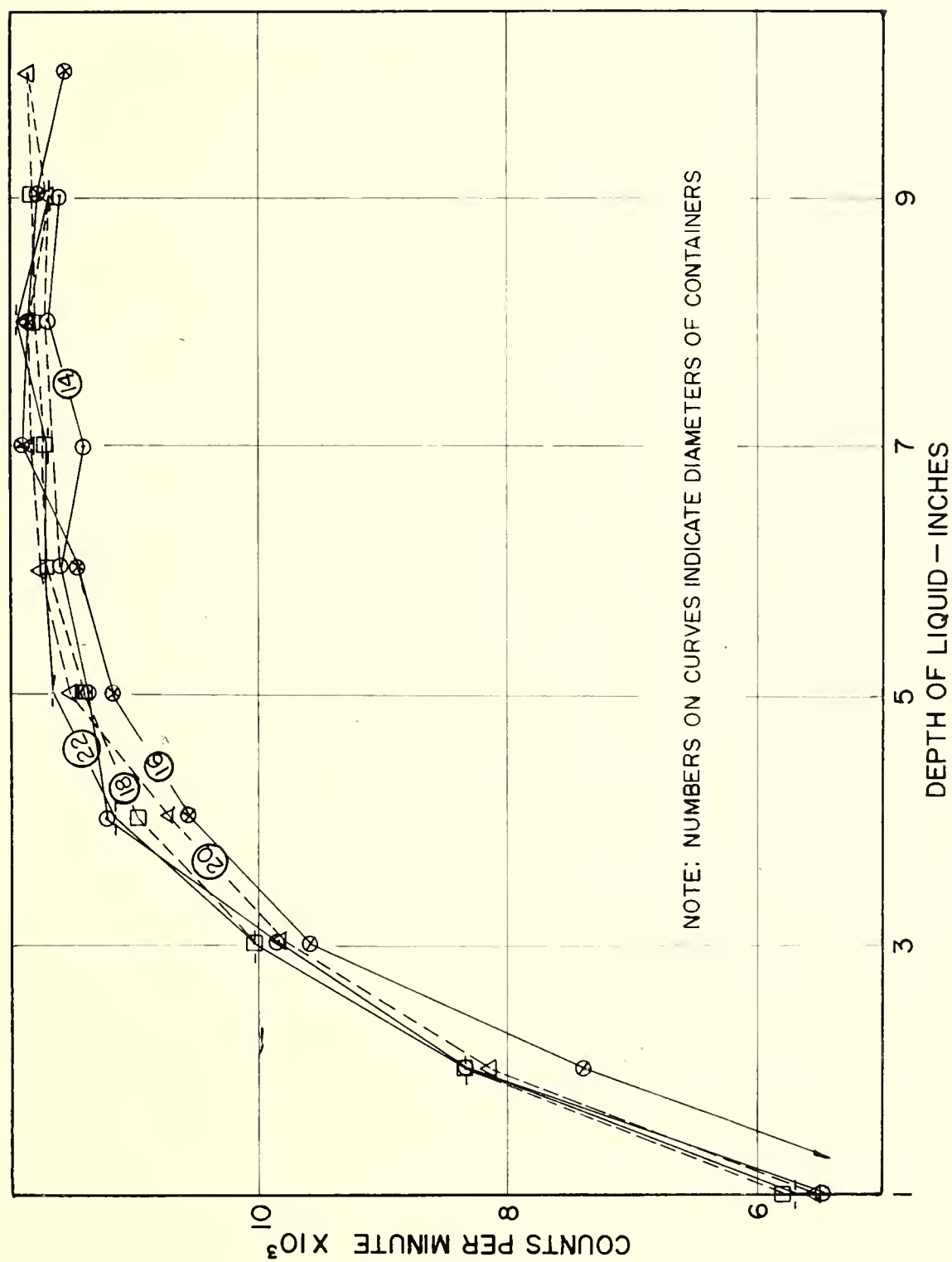


FIG. 4 COUNTS PER MINUTE VERSUS DEPTH FOR EACH CONTAINER FOR CARBON TETRACHLORIDE (99.6 PCF) NUCLEAR CHICAGO

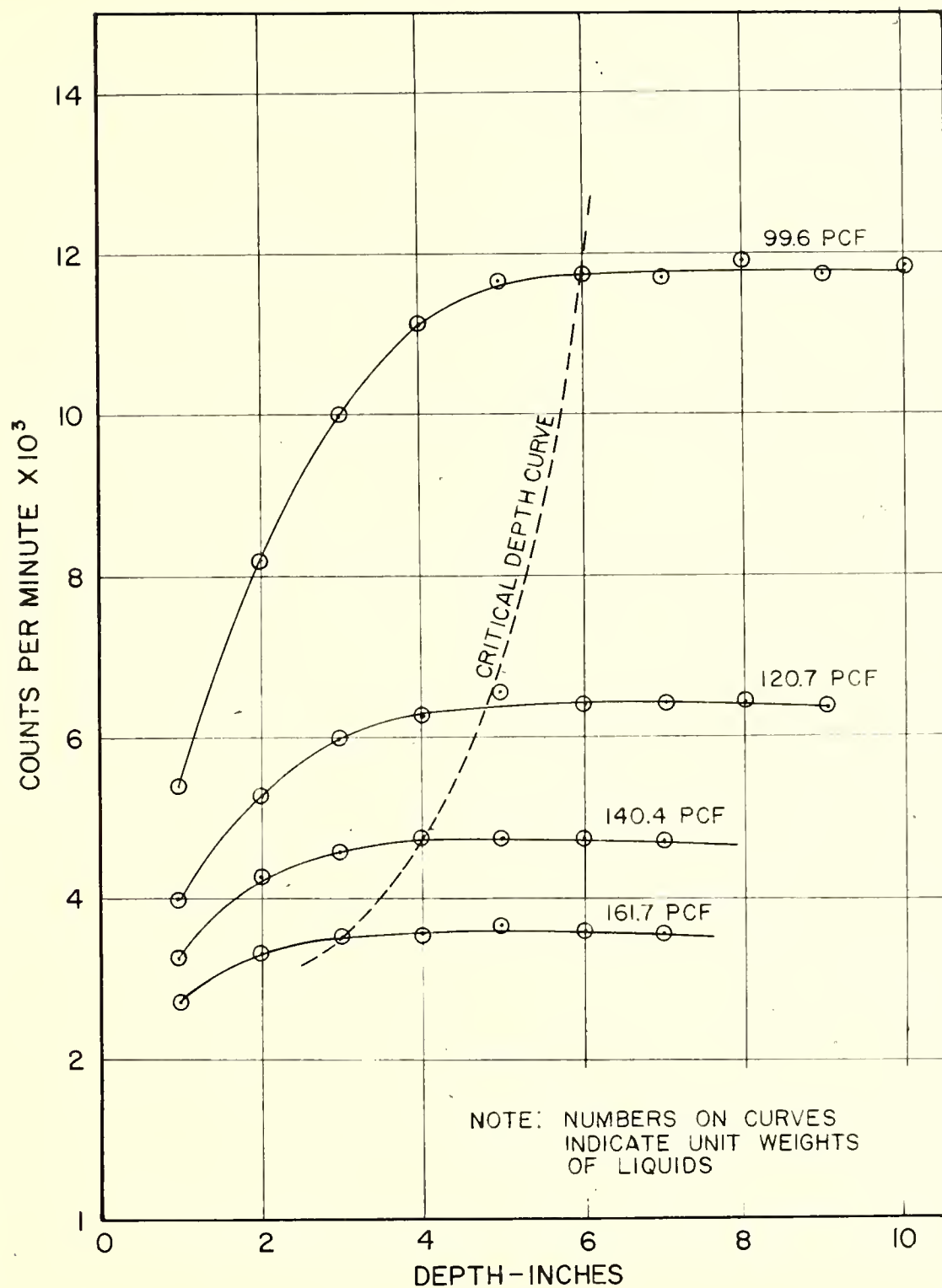


FIG.5 INFLUENCE OF DEPTH OF LIQUID ON COUNTS PER MINUTE FOR SEVERAL UNIT WEIGHTS (20 INCH CONTAINER) NUCLEAR CHICAGO

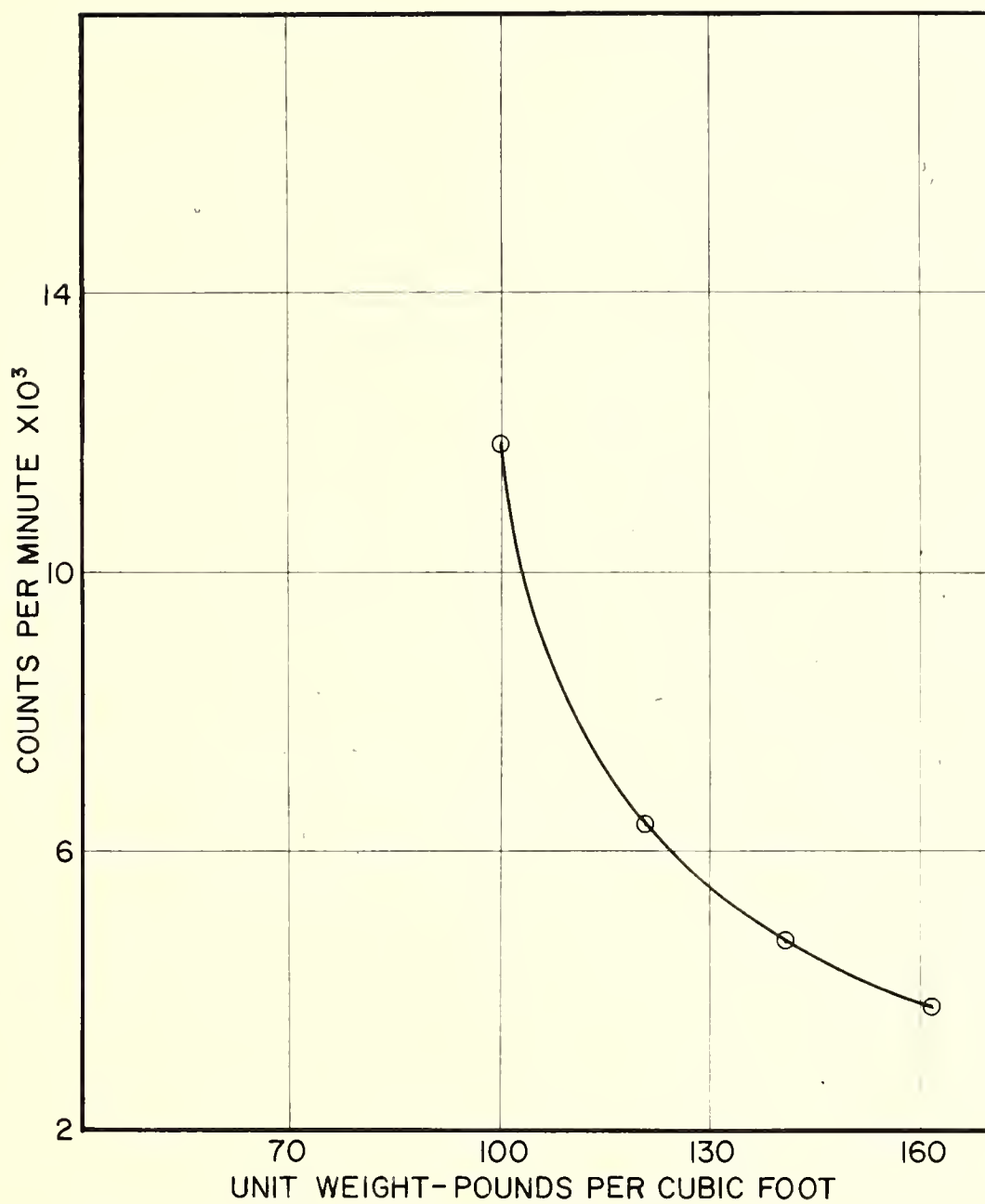


FIG. 6 COUNTS PER MINUTE VERSUS UNIT WEIGHT
OF LIQUIDS (20 INCH CONTAINER)
NUCLEAR CHICAGO

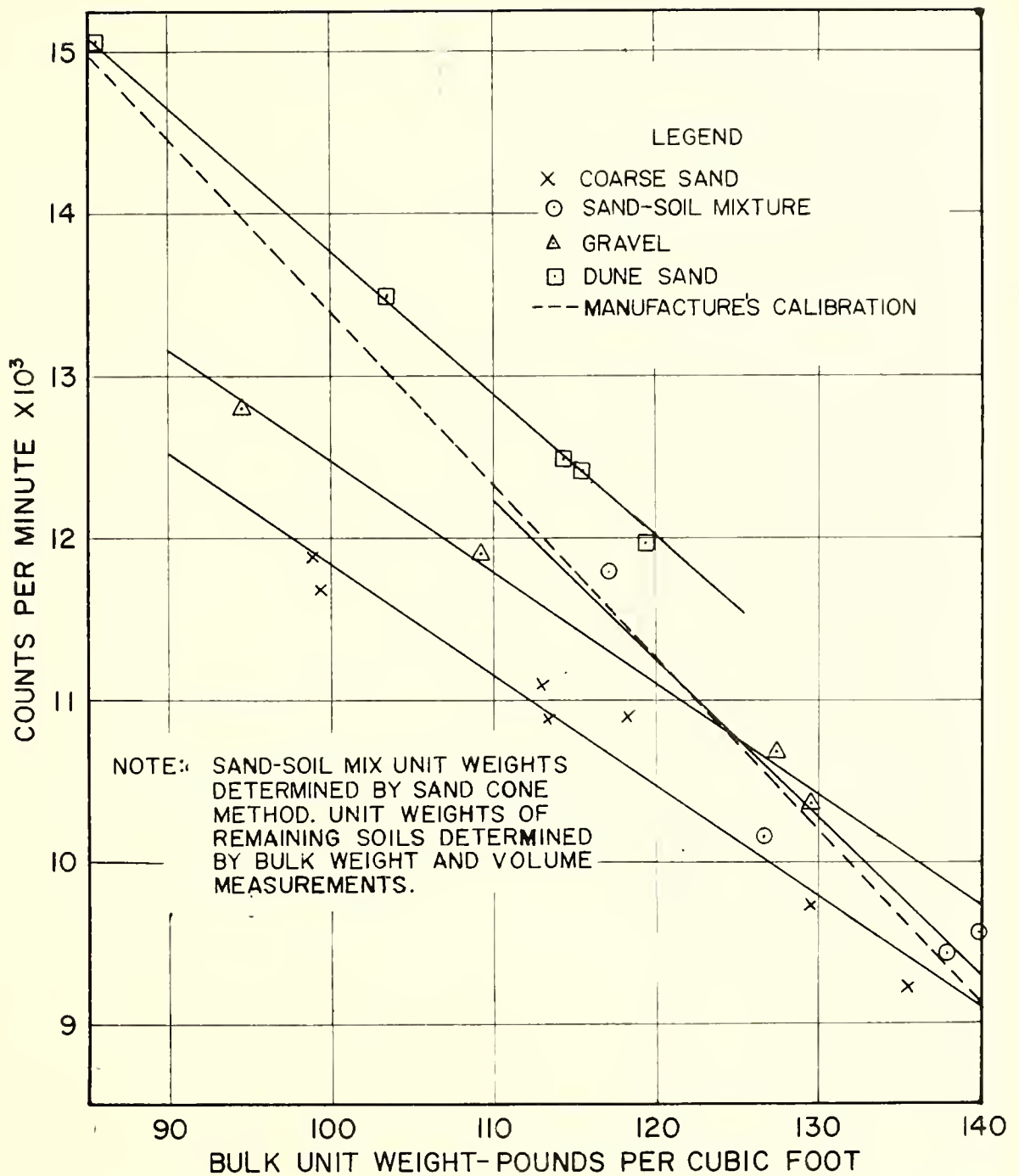


FIG. 7 N-C CALIBRATION CURVE SHOWING SOIL TYPE

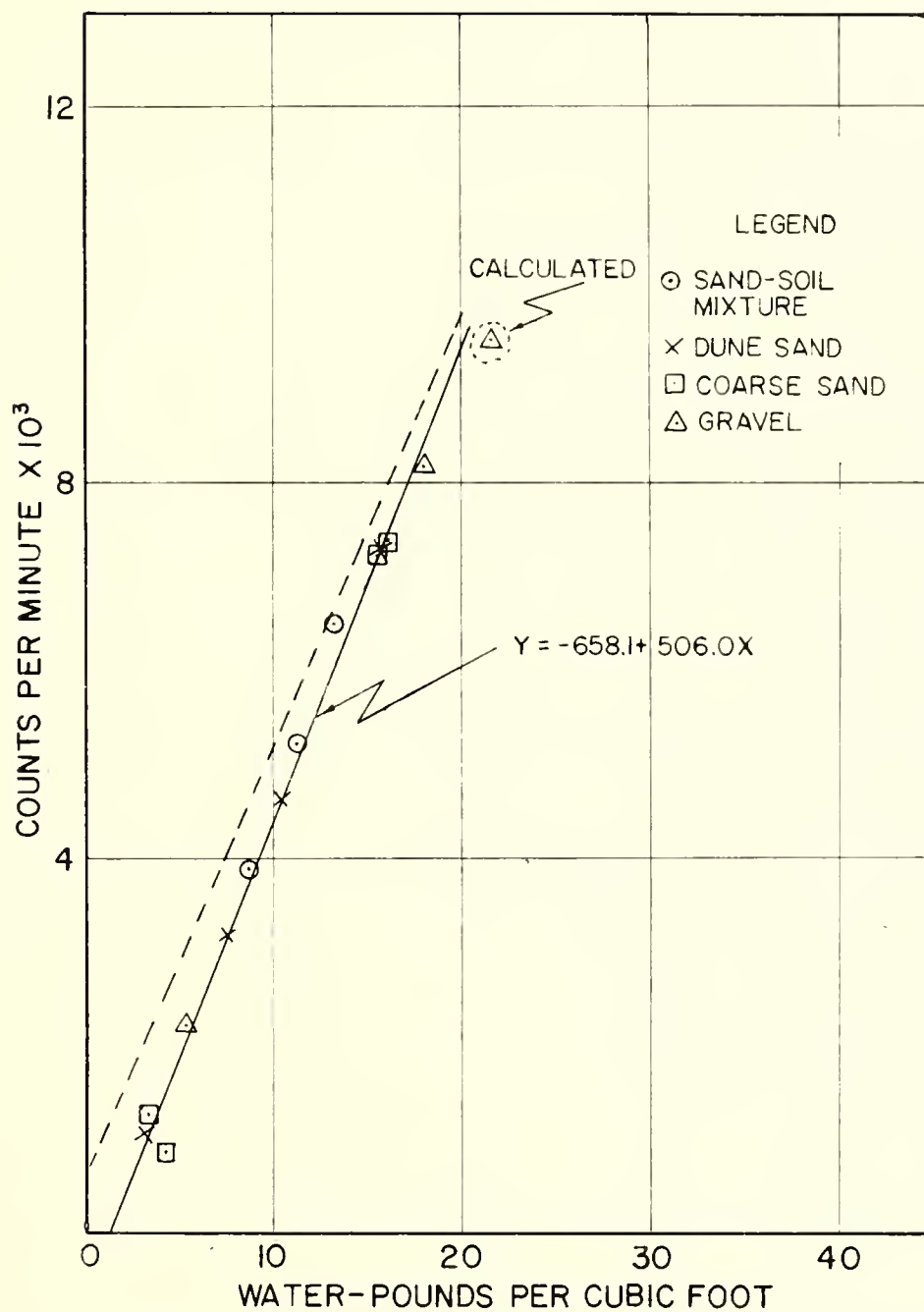


FIG. 8 N-C MOISTURE CALIBRATION CURVE

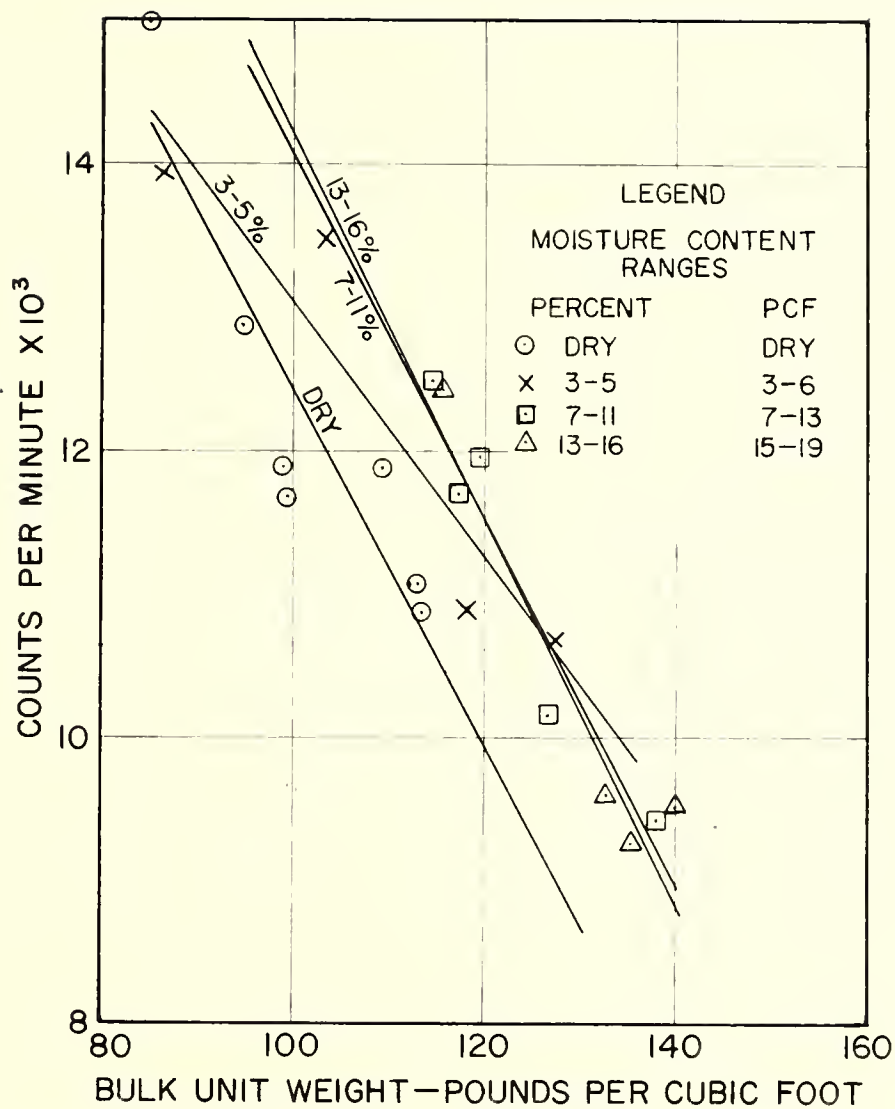


FIG. 9 N-C DENSITY CALIBRATION CURVE
SHOWING EFFECT UPON COUNTS PER
MINUTE OF MOISTURE CONTENT

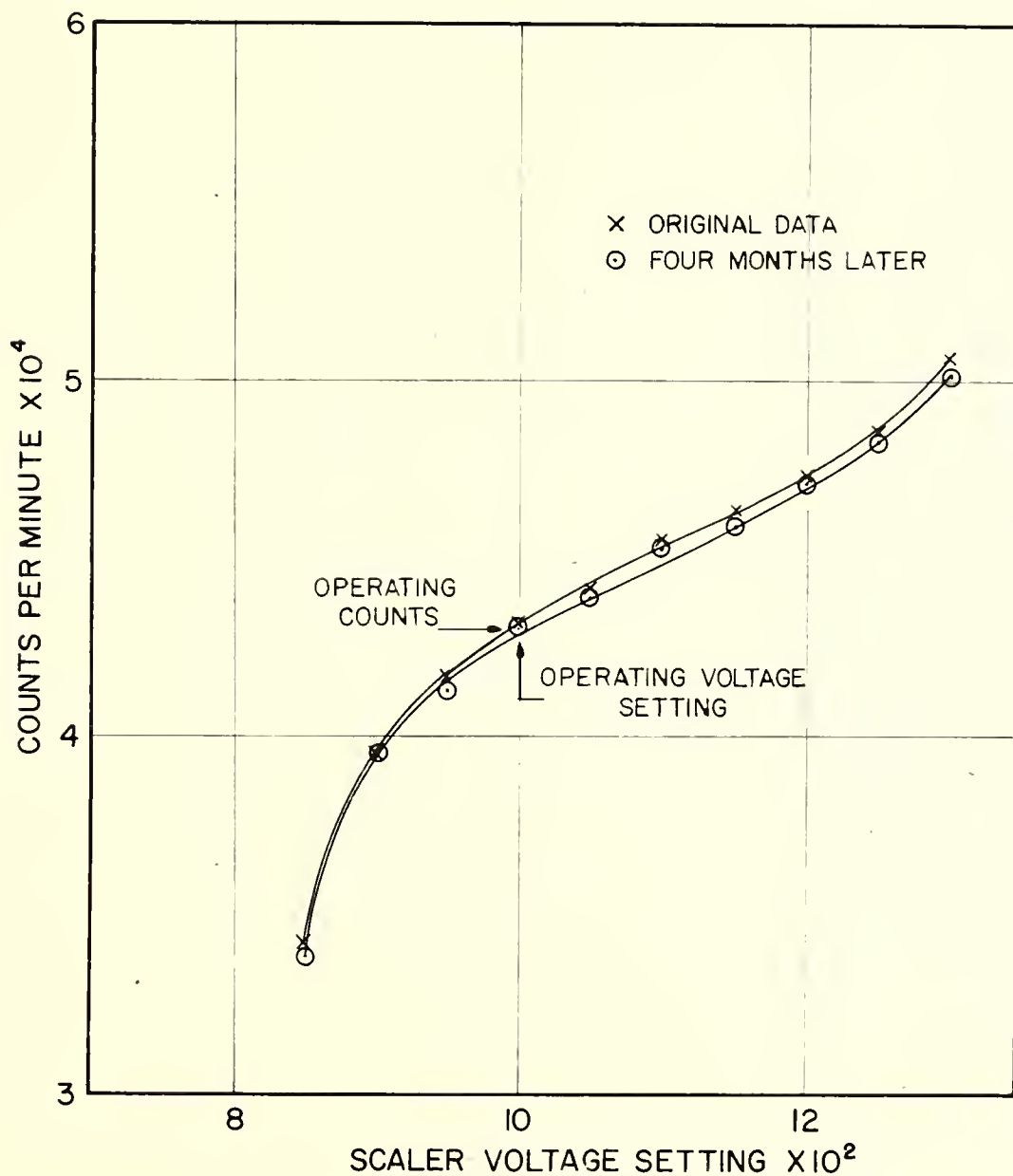


FIG. 10 N-C DENSITY PLATEAU CURVE

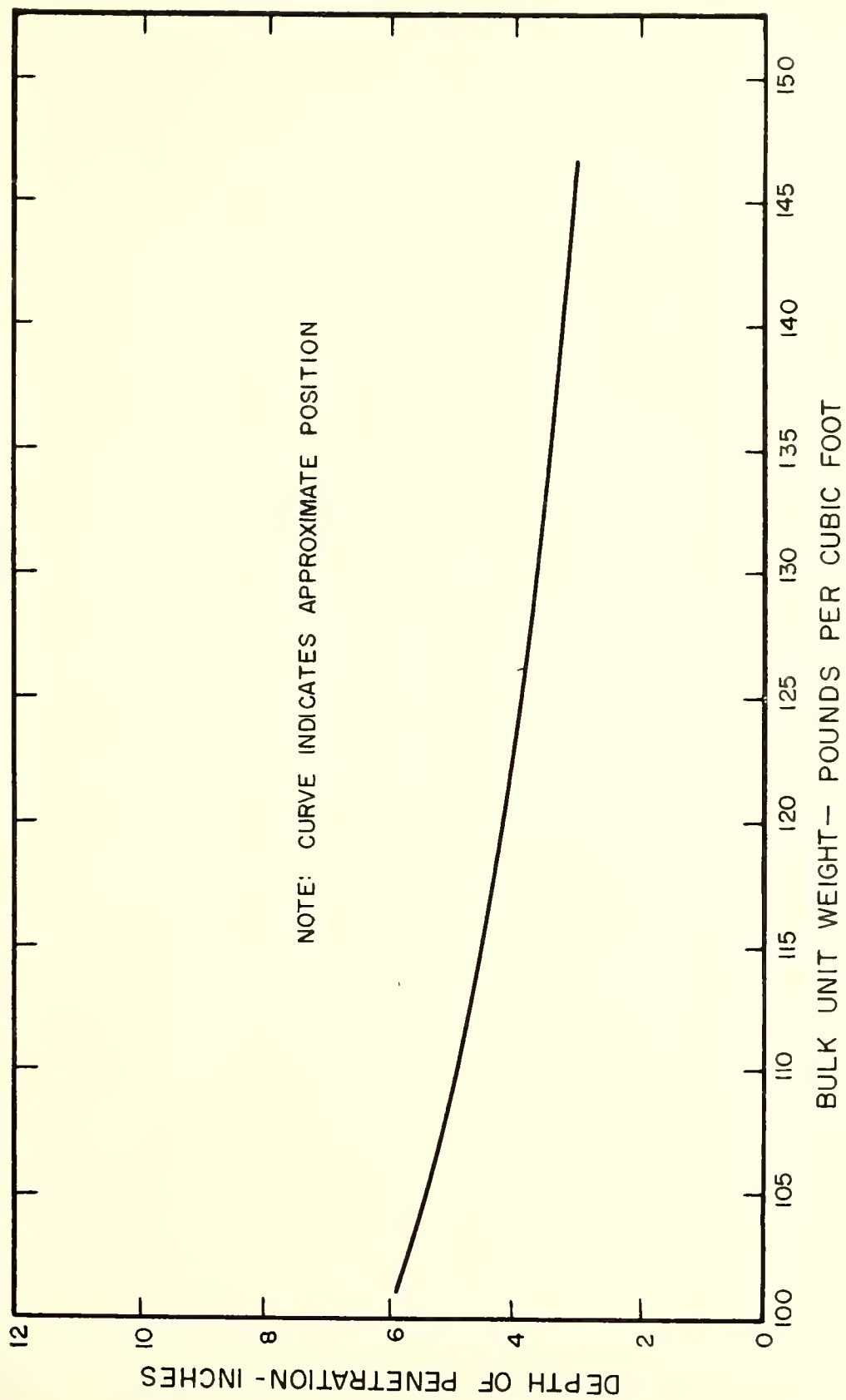


FIG.11 APPROXIMATE DEPTH OF PENETRATION VS. BULK UNIT WEIGHT
—VIATEC INSTRUMENT

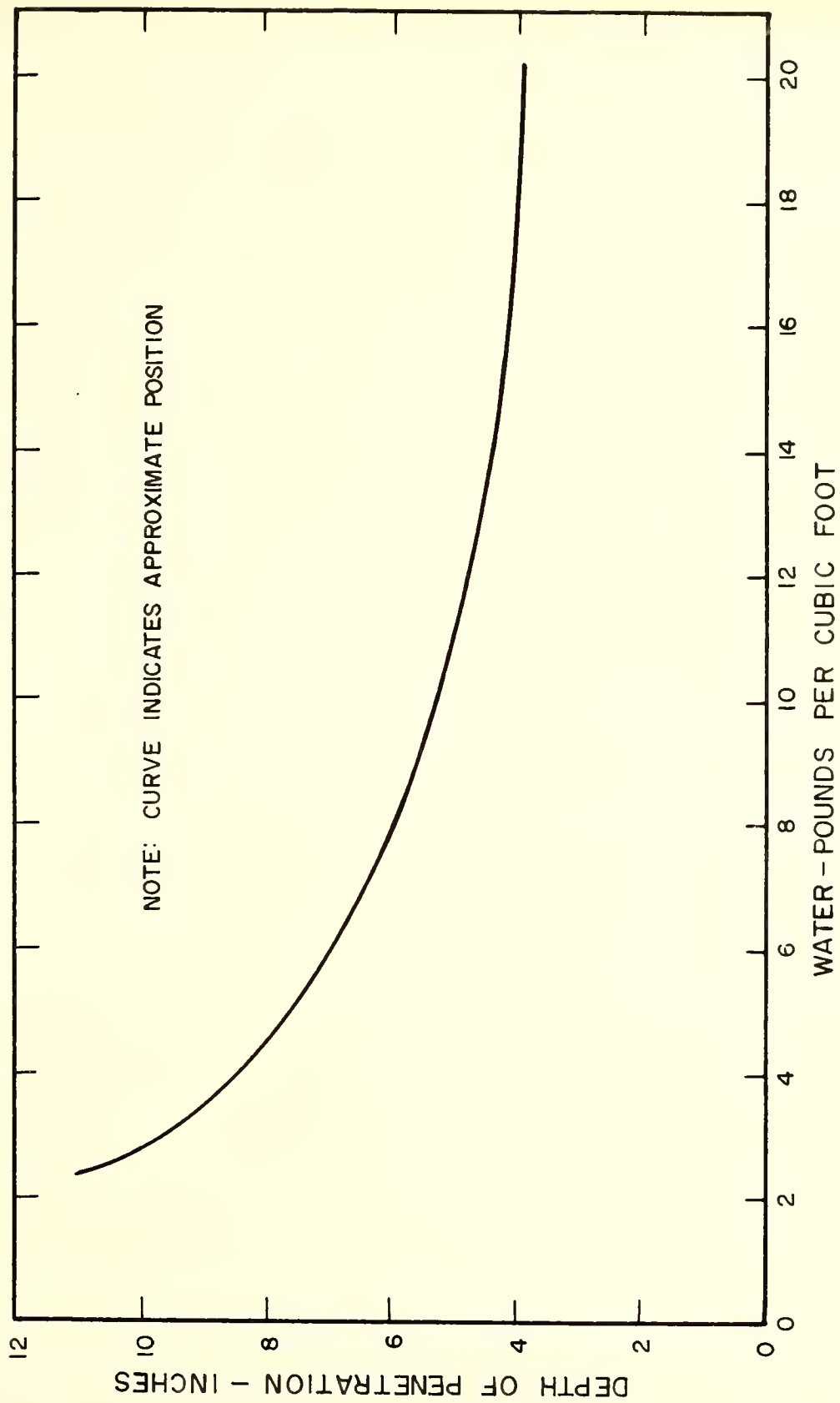


FIG. 12 APPROXIMATE DEPTH OF PENETRATION VS. MOISTURE
—VIATEC INSTRUMENT

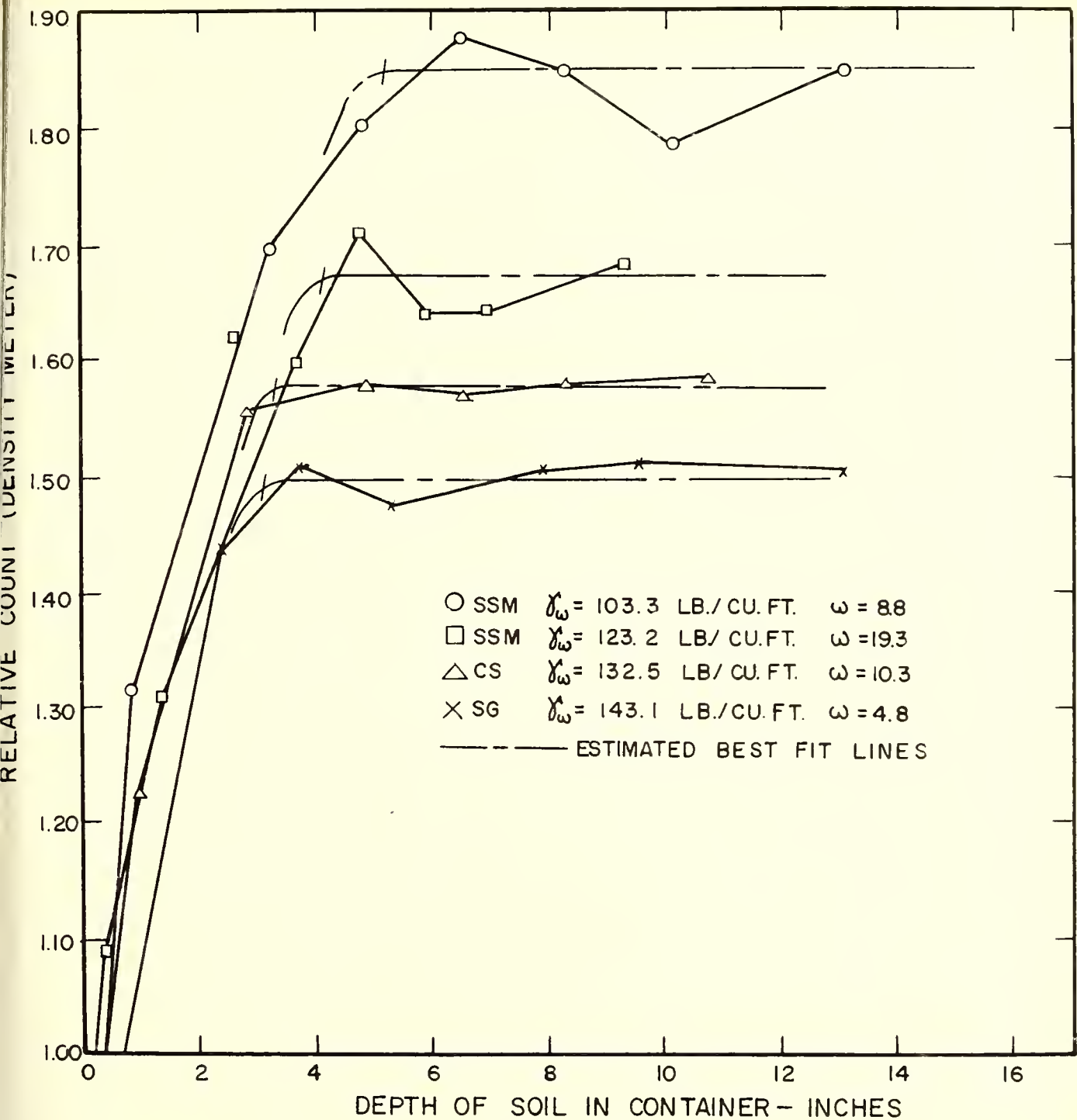


FIG. 13 RELATIONSHIP BETWEEN RELATIVE COUNT AT VARIOUS DEPTHS OF SOIL FOR GIVEN DENSITIES

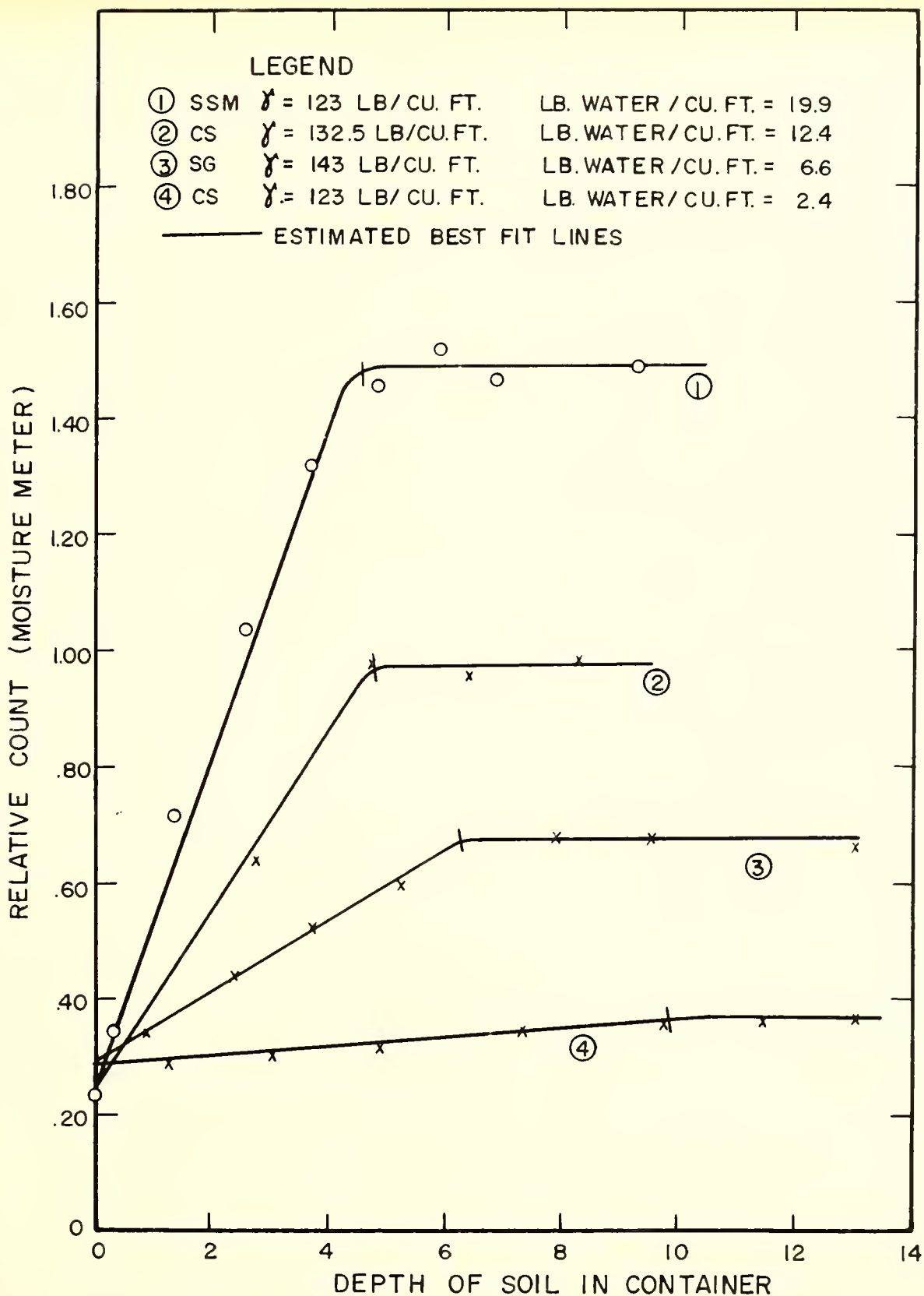


FIG. 14 RELATIONSHIP BETWEEN RELATIVE COUNT AT VARIOUS DEPTHS OF SOIL FOR GIVEN WEIGHT OF WATER PER UNIT VOLUME

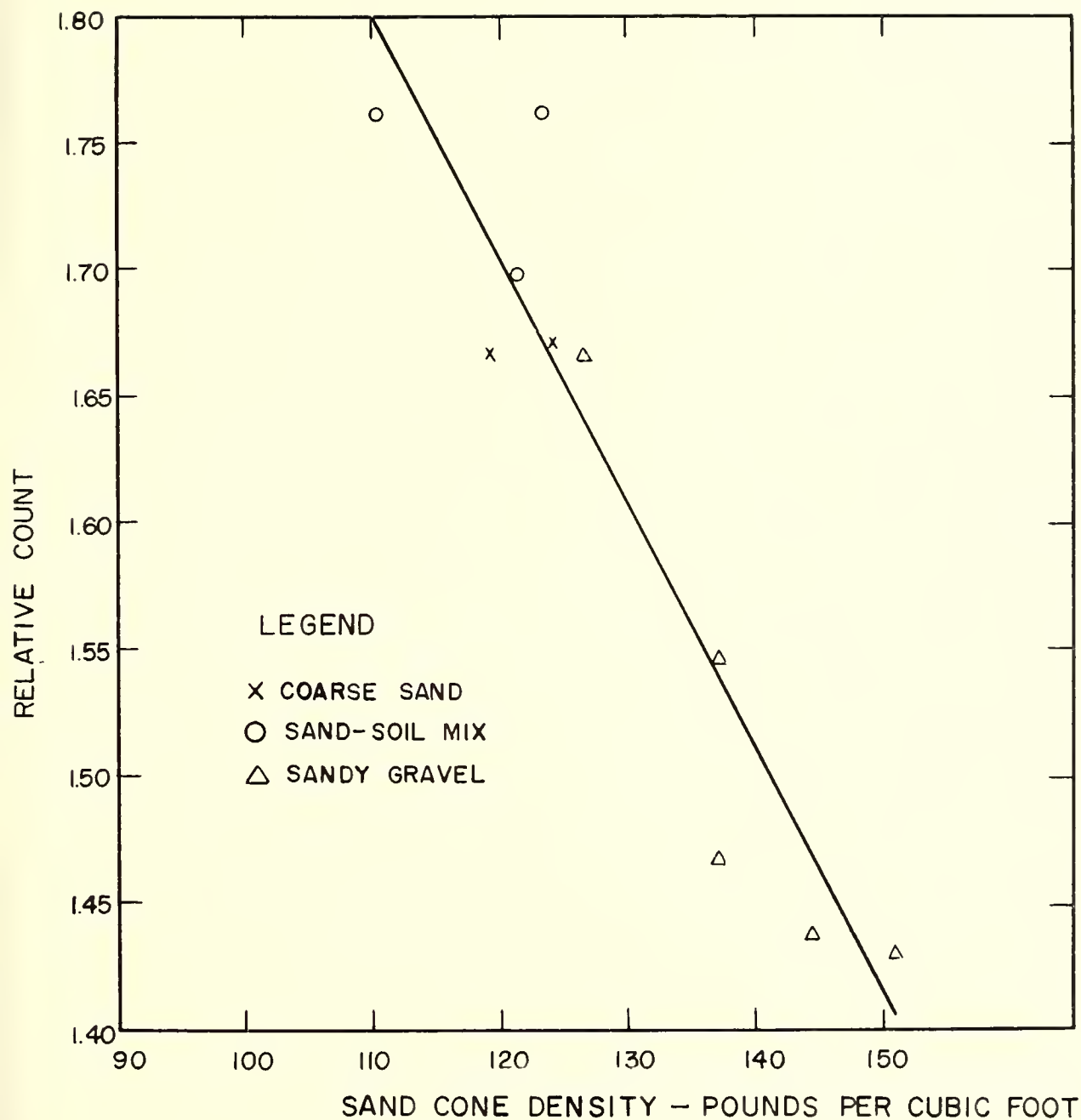


FIG 15 VIATEC DENSITY CALIBRATION CURVE SHOWING
SAND CONE DENSITY VERSUS AVERAGE OF
LAYER RELATIVE COUNT

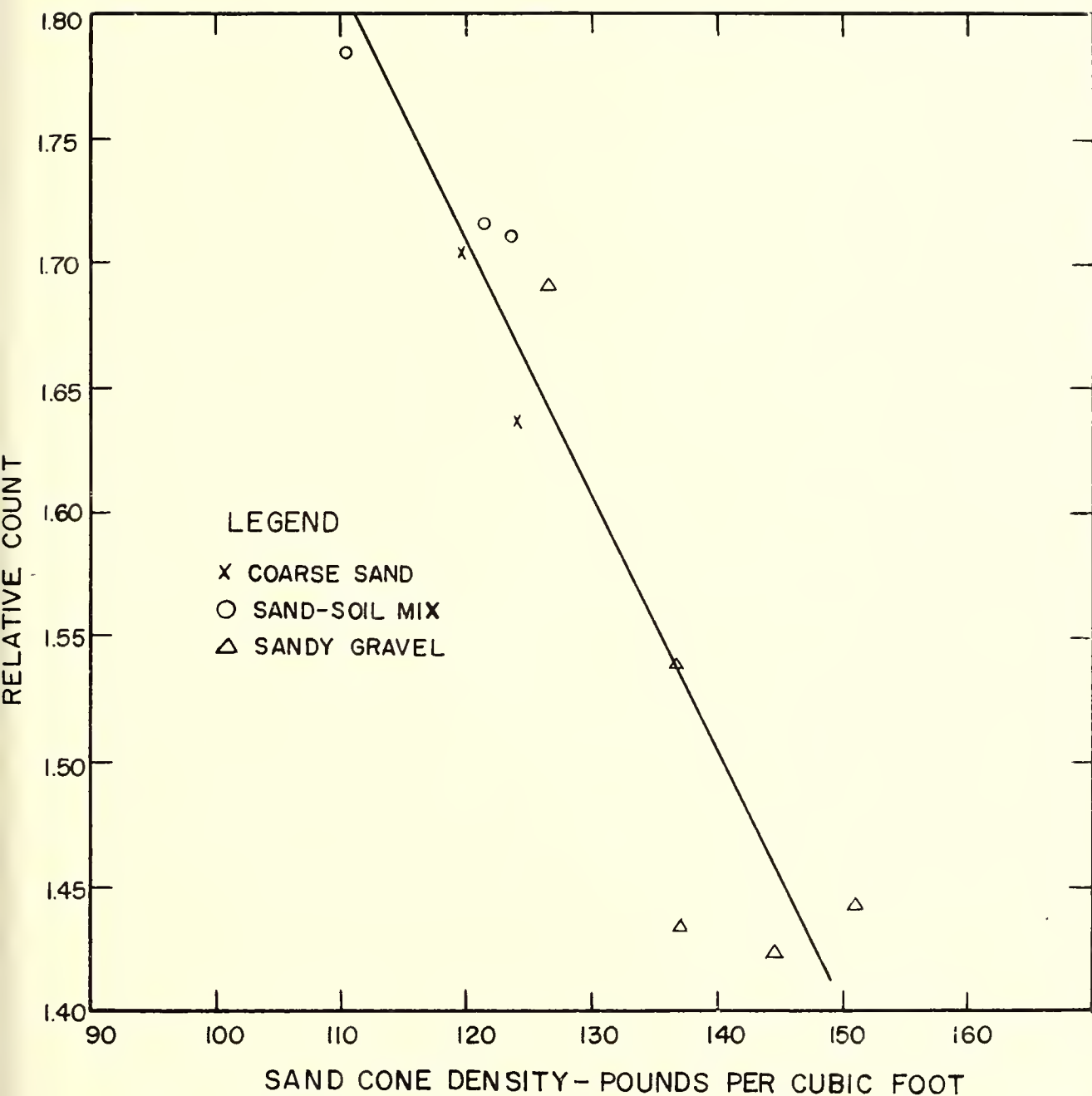


FIG. 16 VIATEC DENSITY CALIBRATION CURVE SHOWING SAND CONE DENSITY VERSUS RELATIVE COUNT OF LAST LAYER TESTED

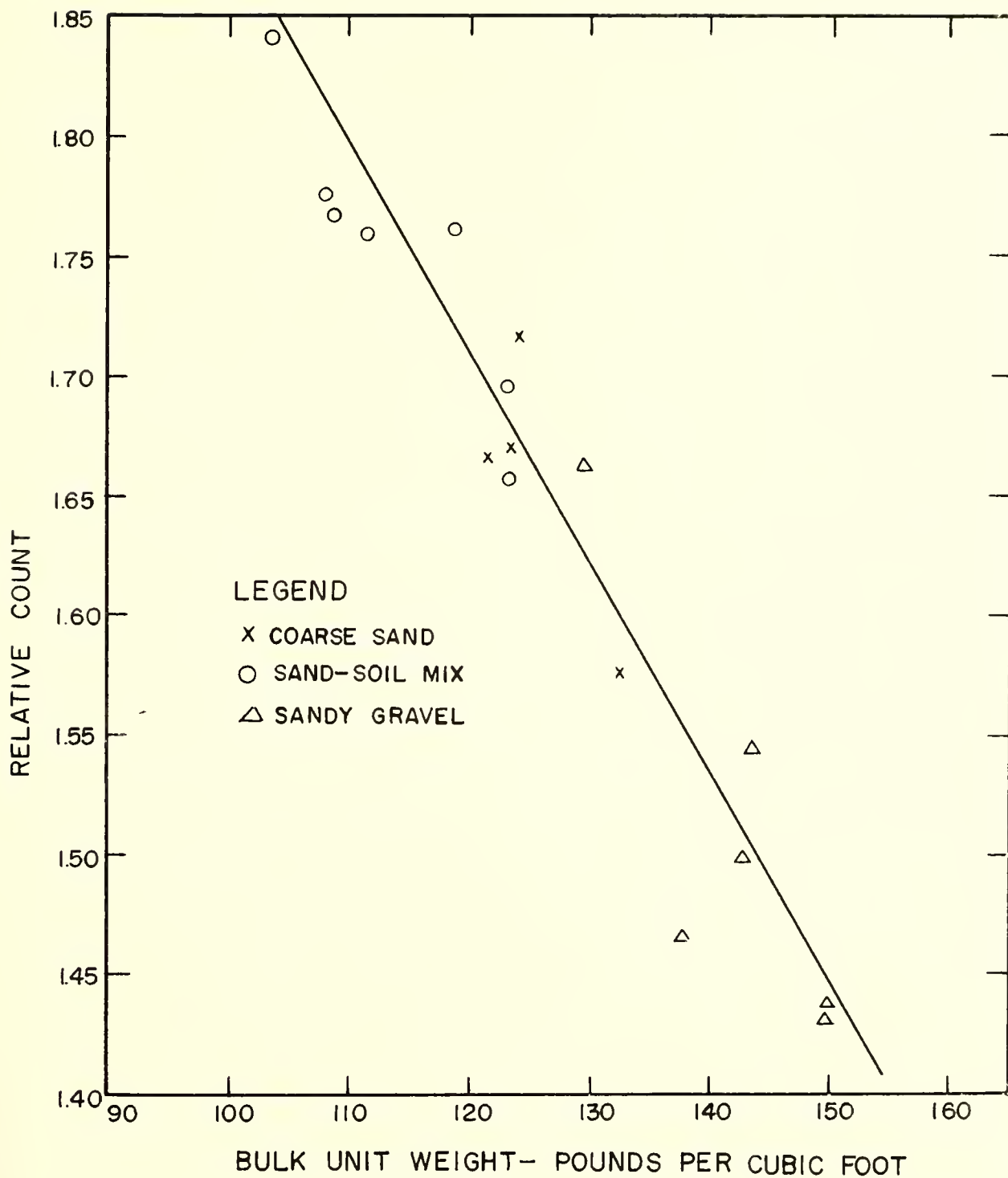


FIG. 17 VIATEC DENSITY CALIBRATION CURVE SHOWING AVERAGE OF LAYER DENSITIES BY BULK METHOD VERSUS AVERAGE OF LAYER RELATIVE COUNTS

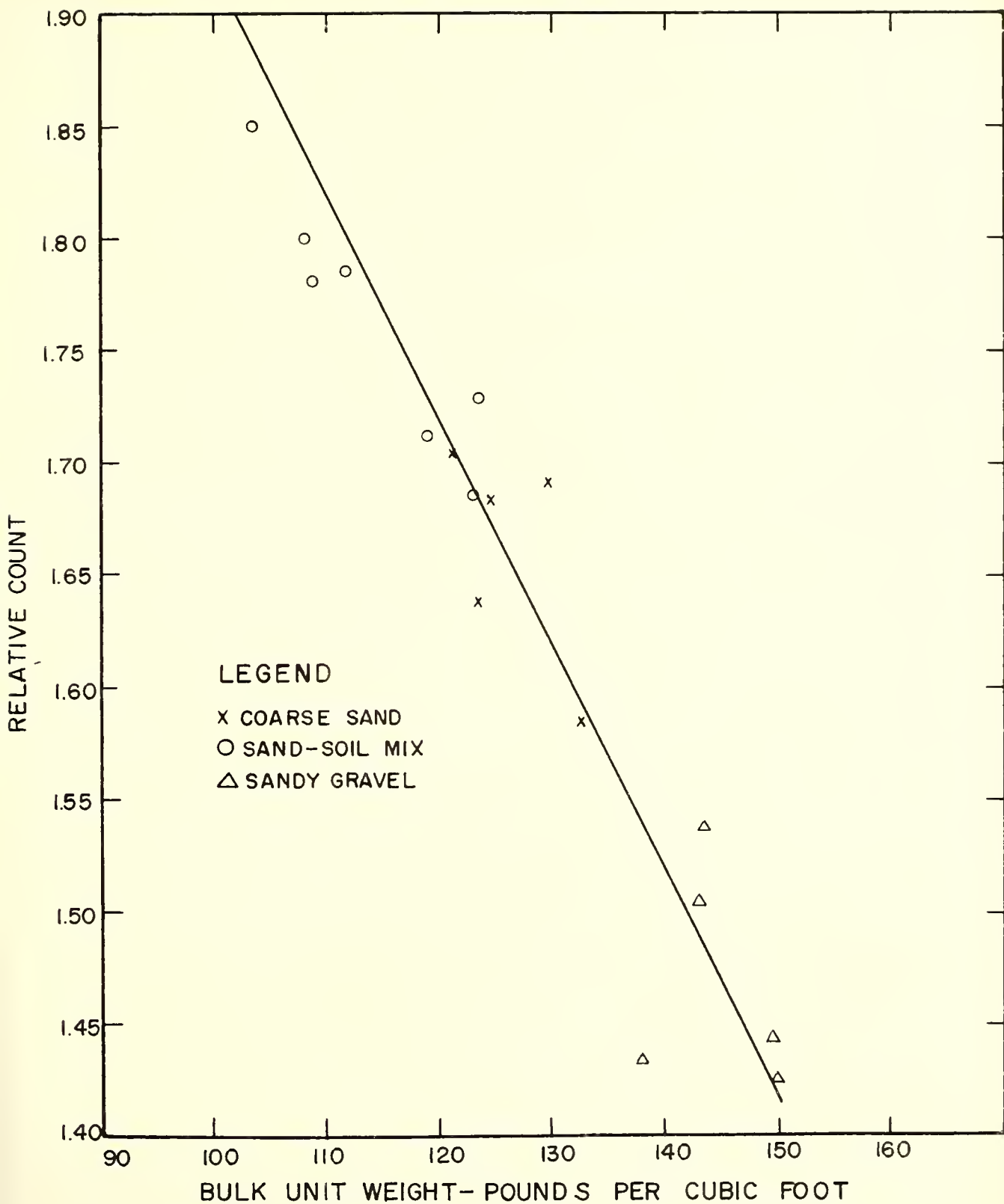


FIG. 18 VIATEC DENSITY CALIBRATION CURVE SHOWING AVERAGE OF LAYER DENSITIES BY BULK METHOD VERSUS RELATIVE COUNT OF LAST LAYER TESTED.

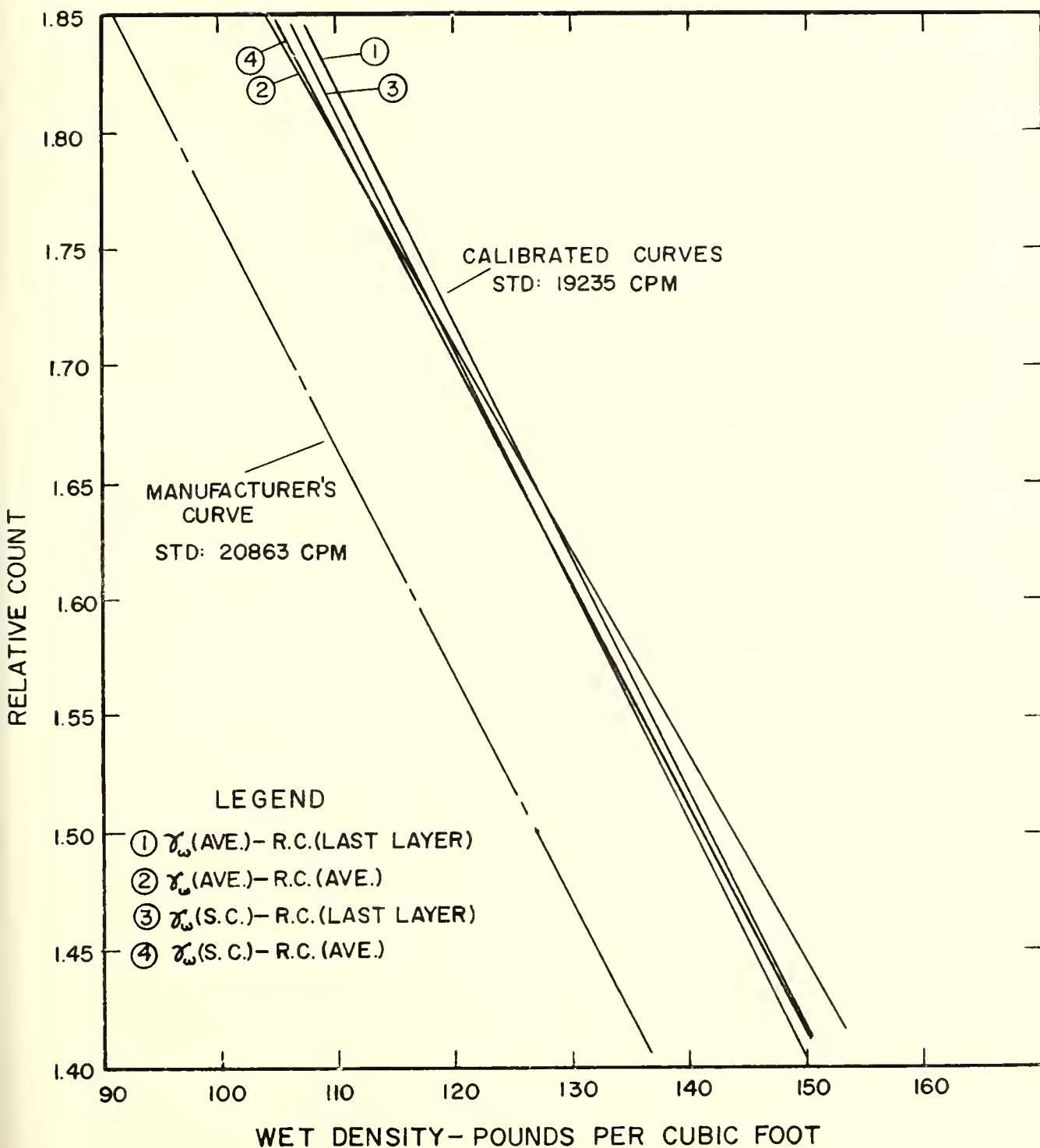


FIG. 19 COMPARISON OF VARIOUS DENSITY CALIBRATION METHODS TO VIATEC CURVE

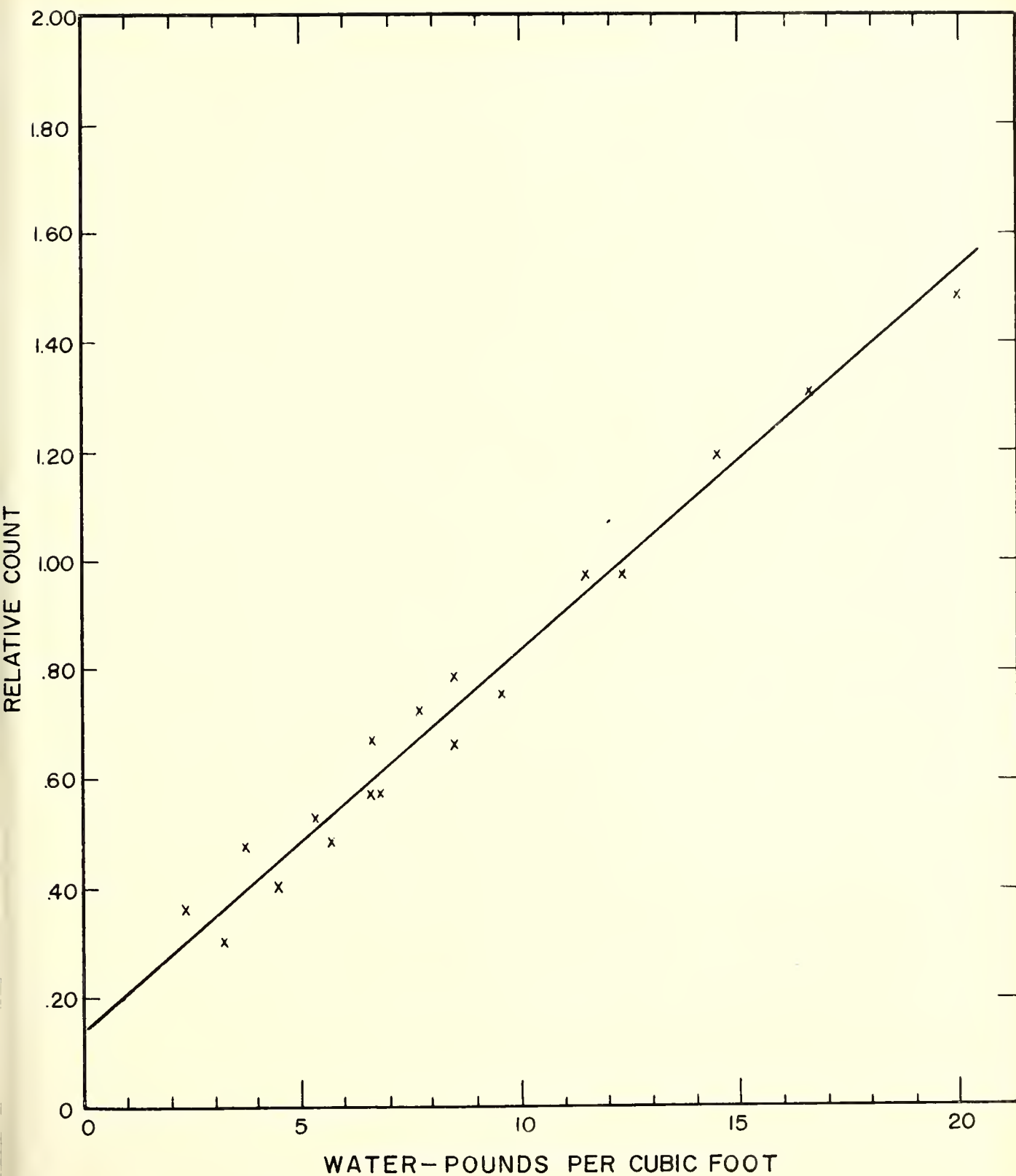


FIG. 20 VIATEC MOISTURE CALIBRATION CURVE

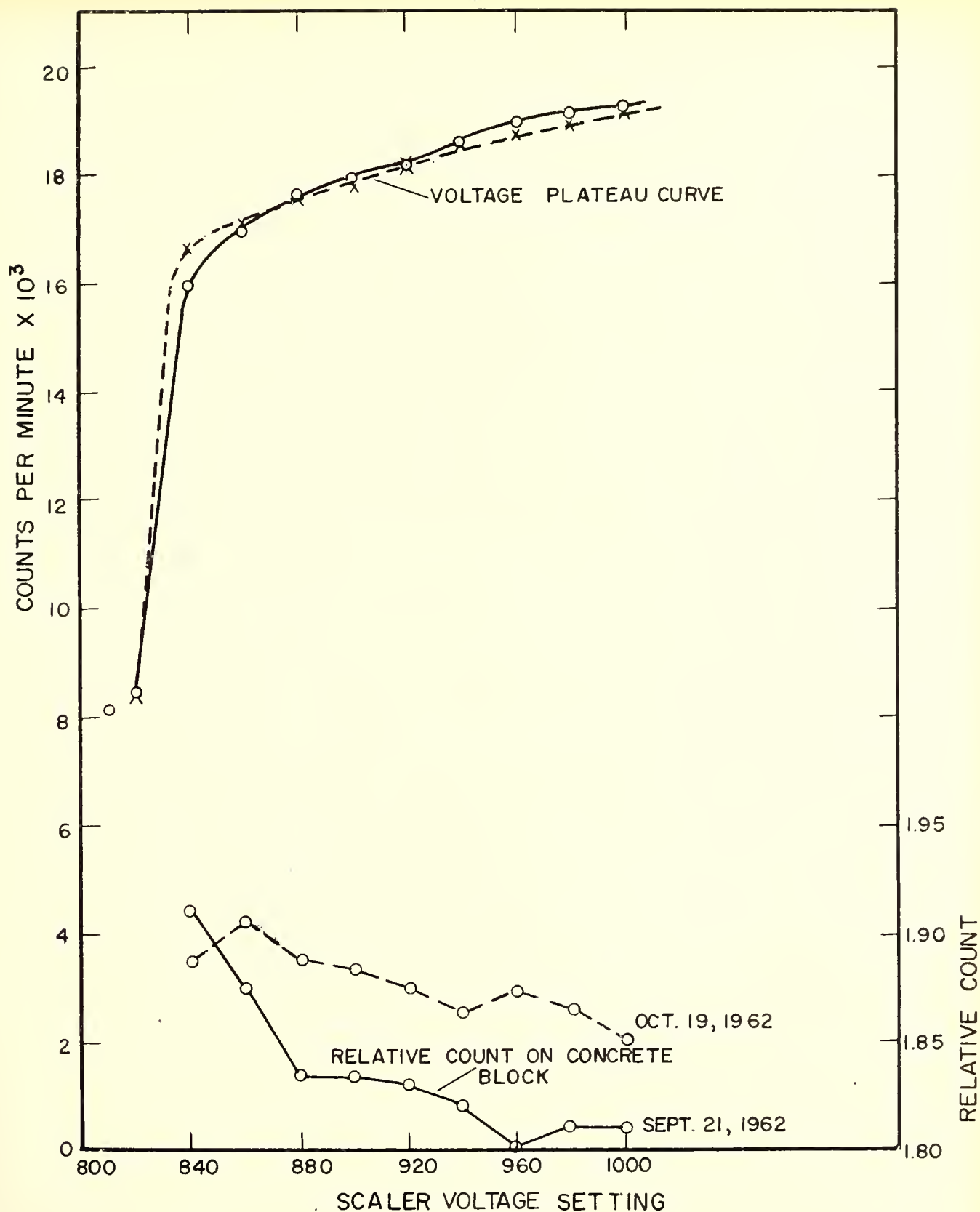


FIG. 21 VIATEC PLATEAU CURVE SHOWING STABILITY OF RELATIVE COUNT ON STANDARD BLOCK OVER VARIABLE OPERATING VOLTAGES

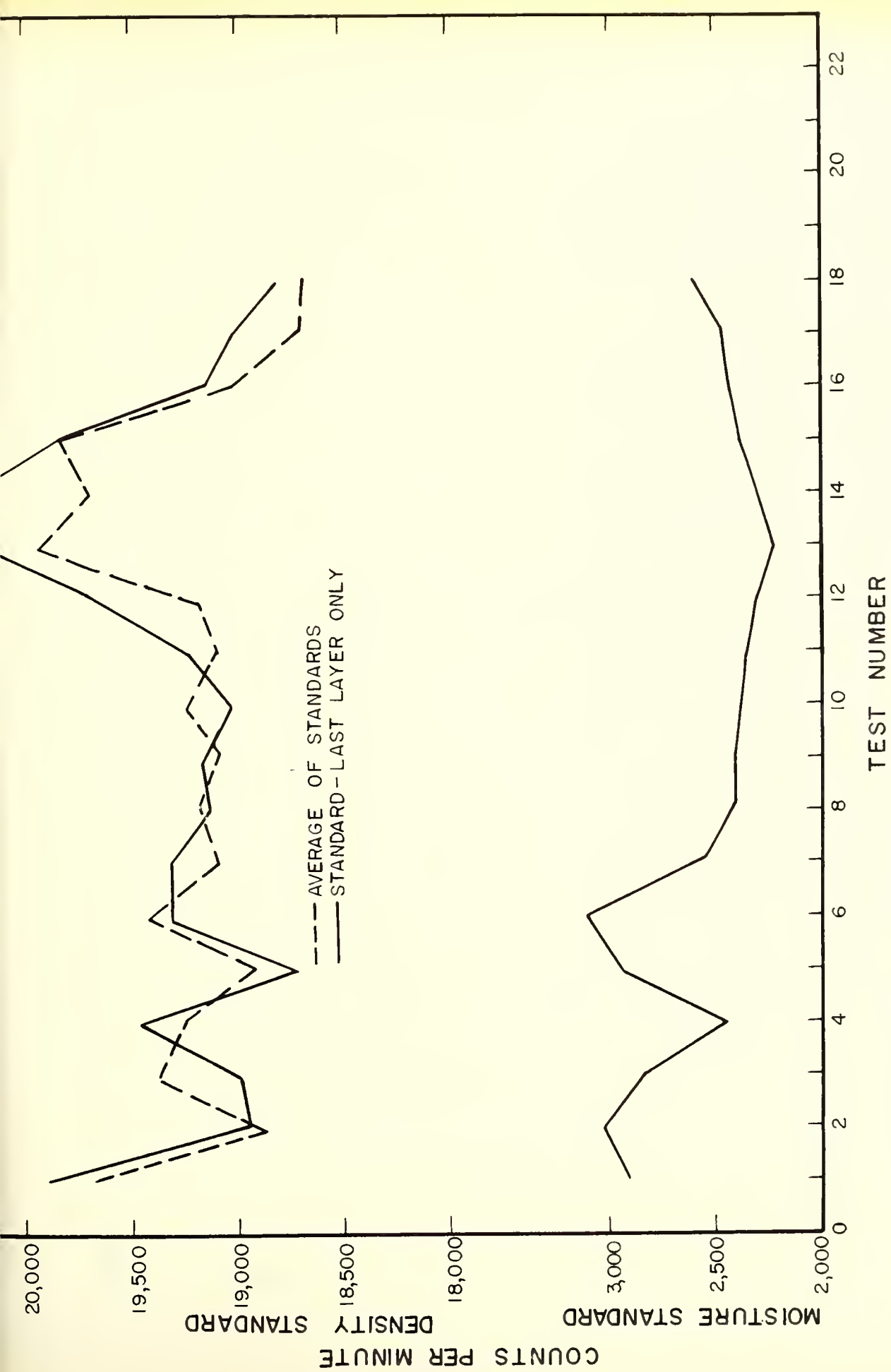


FIG. 22 VARIABILITY OF STANDARD COUNTS

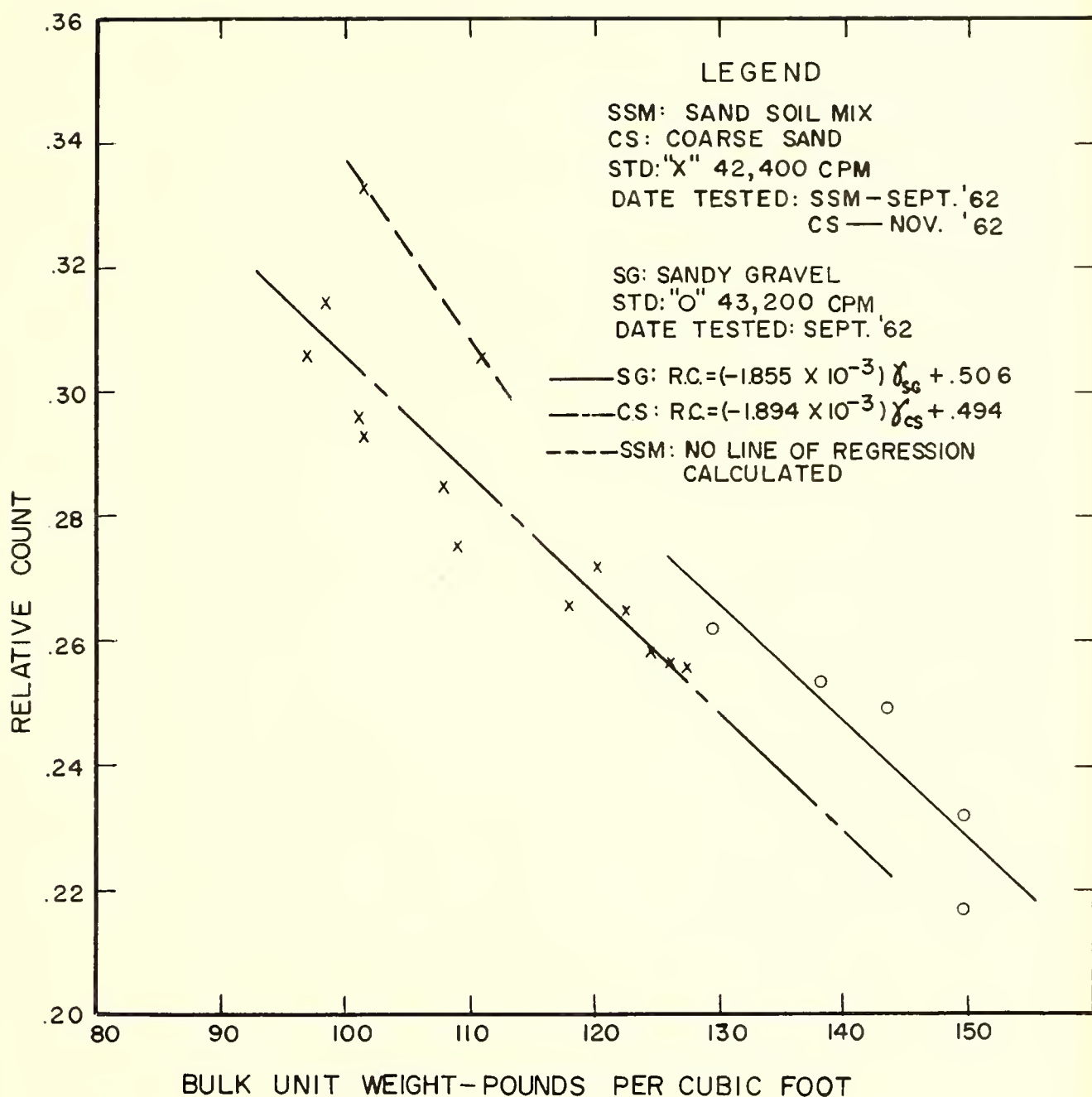


FIG. 23 N-C CALIBRATION CURVE SHOWING SOIL TYPE AND VARIANCE IN STANDARDS

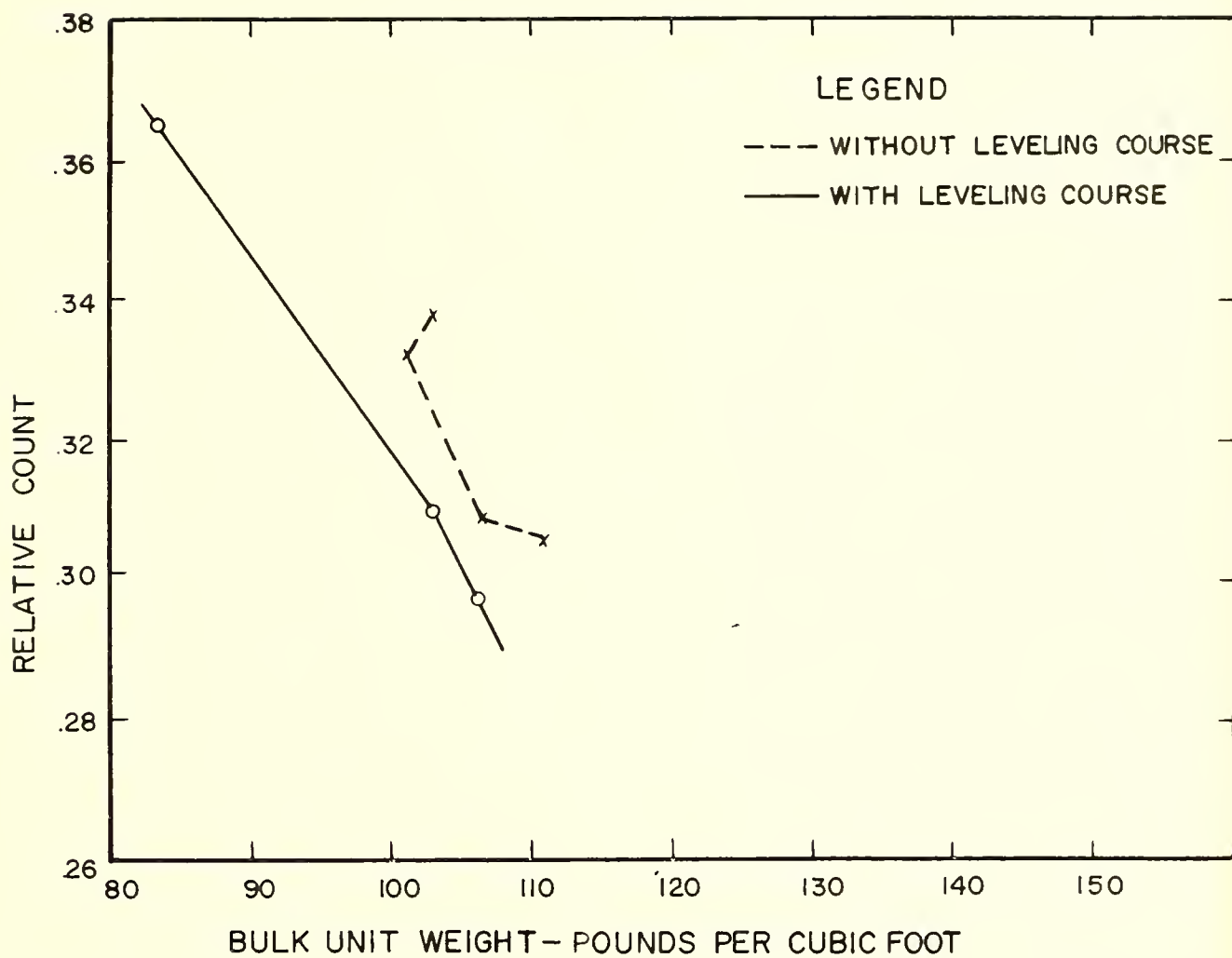


FIG.24 N-C CALIBRATION CURVE SHOWING EFFECT OF LEVELING COURSE UNDER INSTRUMENT FOR SAND SOIL MIX (SSM)

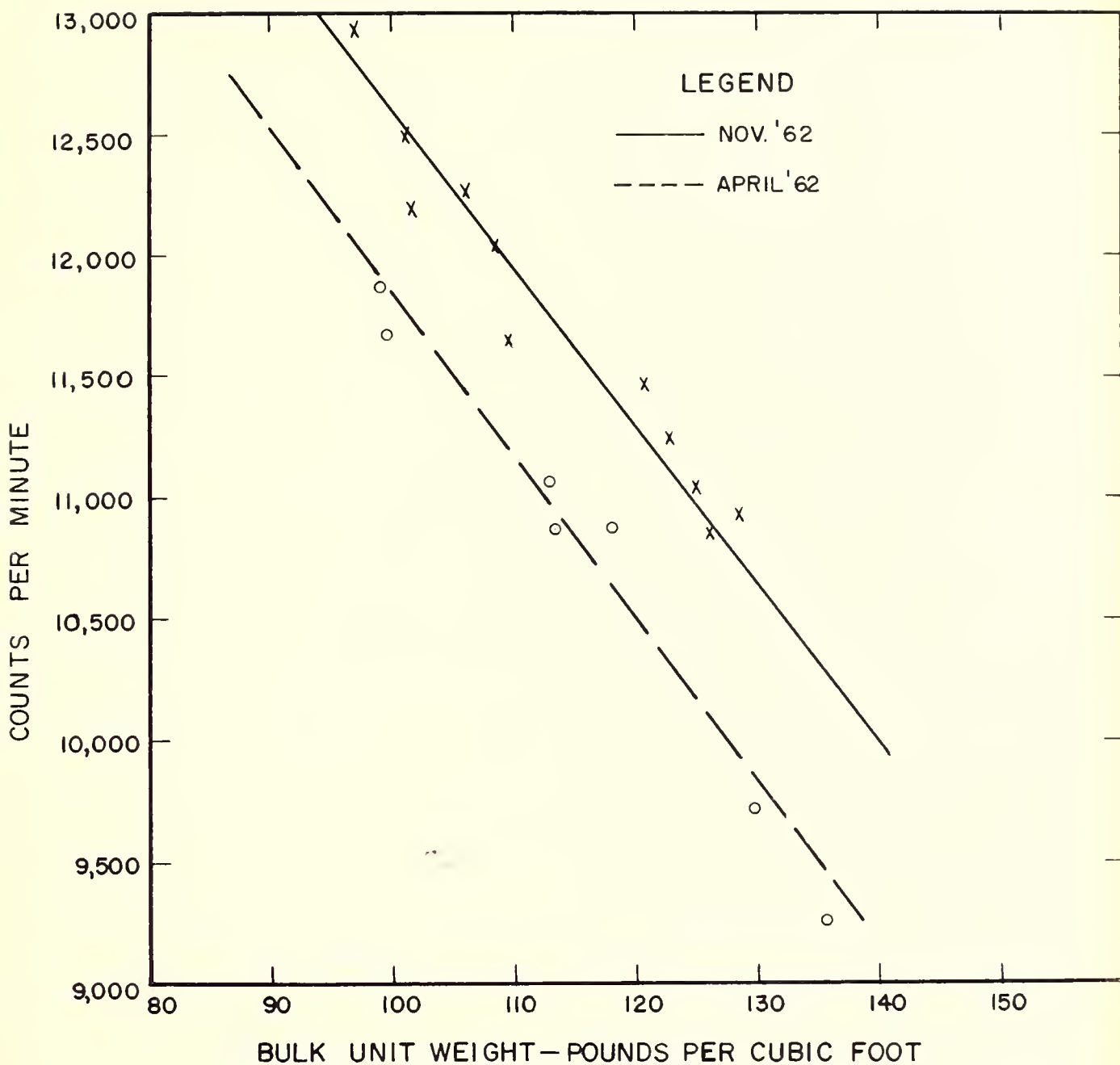


FIG. 25 N-C CALIBRATION CURVE FOR COARSE SAND
SHOWING COUNTS PER MINUTE VARIANCE
BETWEEN TESTING INTERVALS

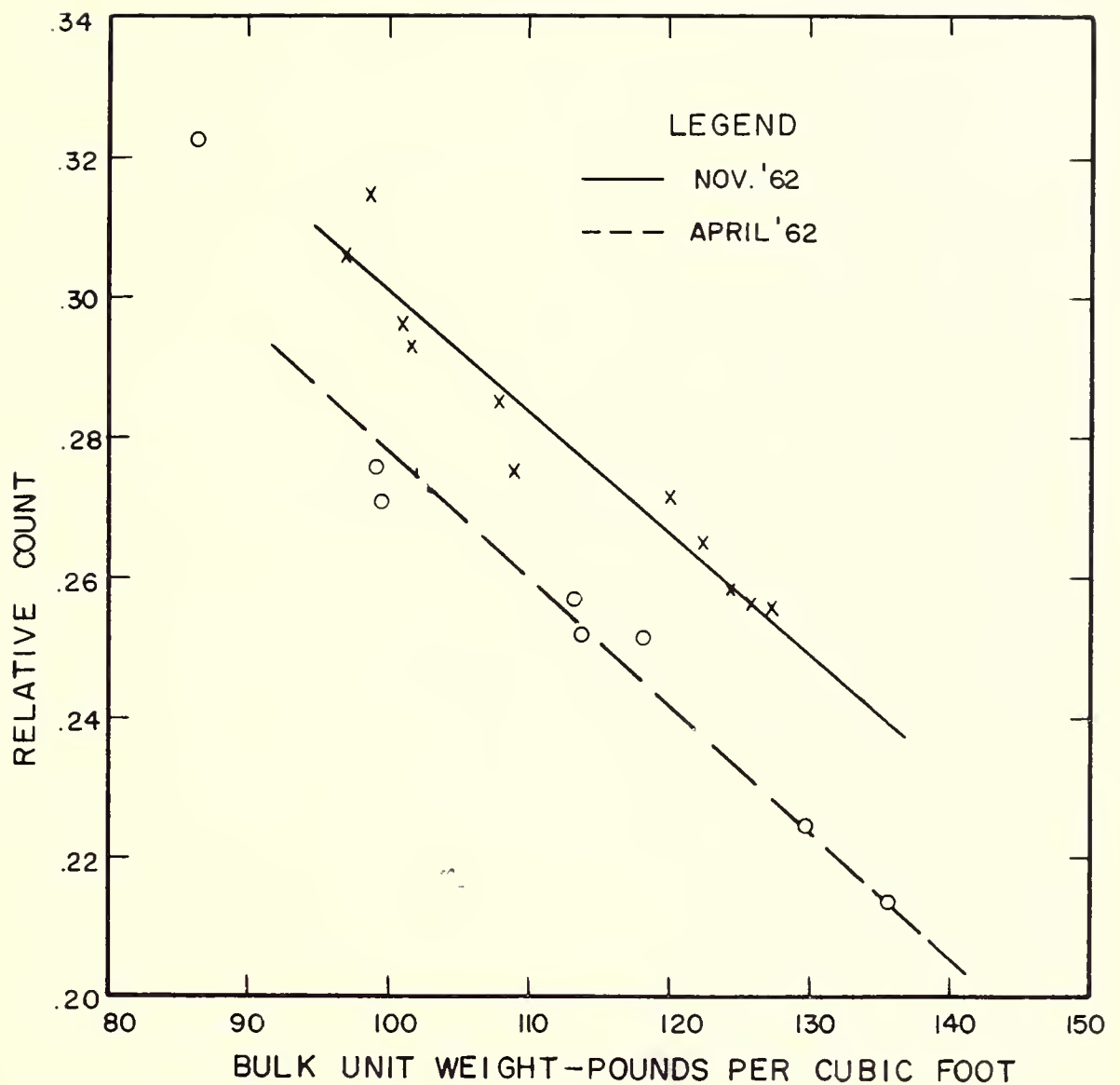


FIG.26 N-C CALIBRATION CURVE FOR COARSE SAND
SHOWING RELATIVE COUNT VARIANCE BETWEEN
TESTING INTERVALS

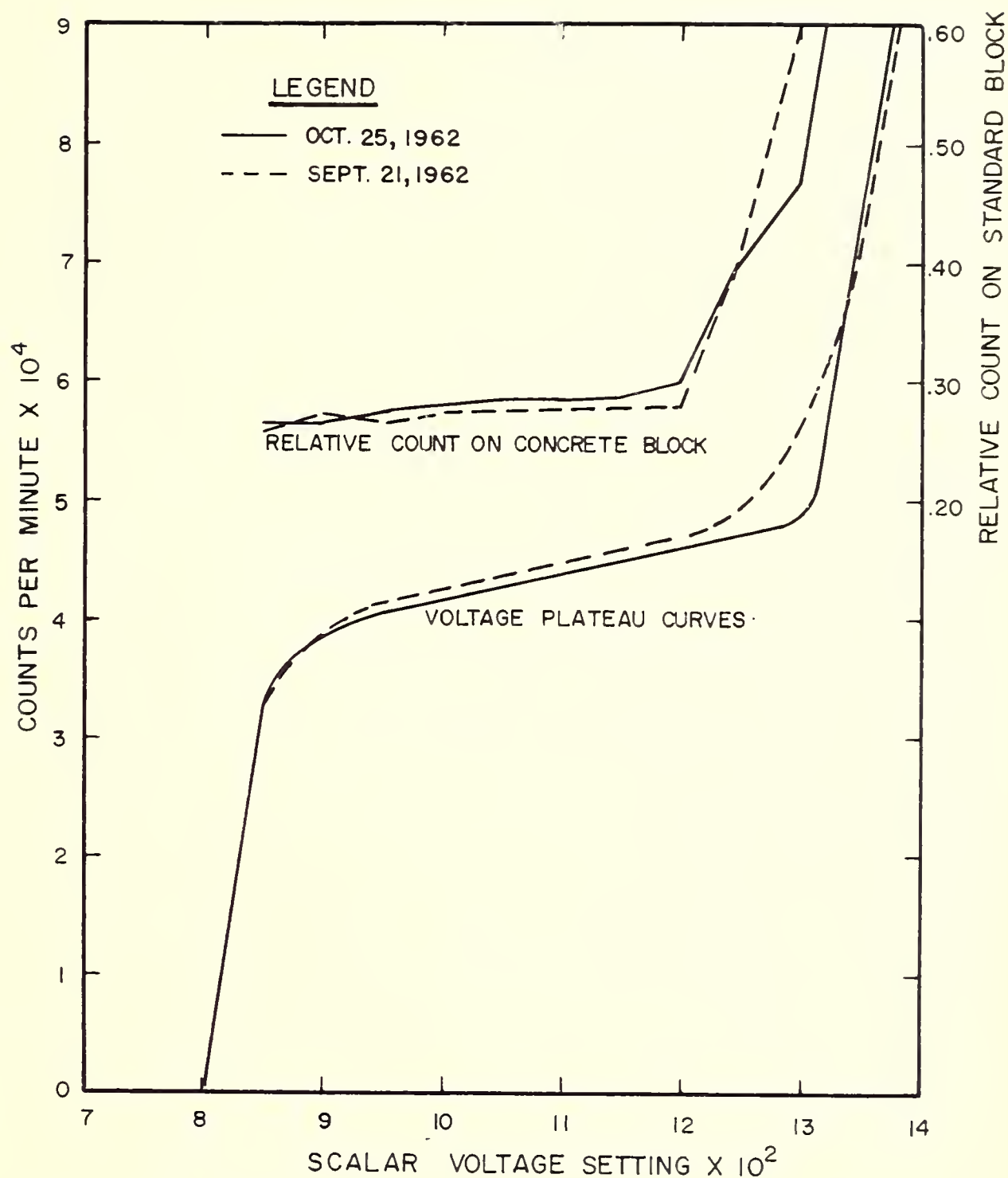


FIG. 27 N-C PLATEAU CURVE SHOWING STABILITY OF RELATIVE COUNT ON STANDARD BLOCK OVER VARIABLE OPERATING VOLTAGES

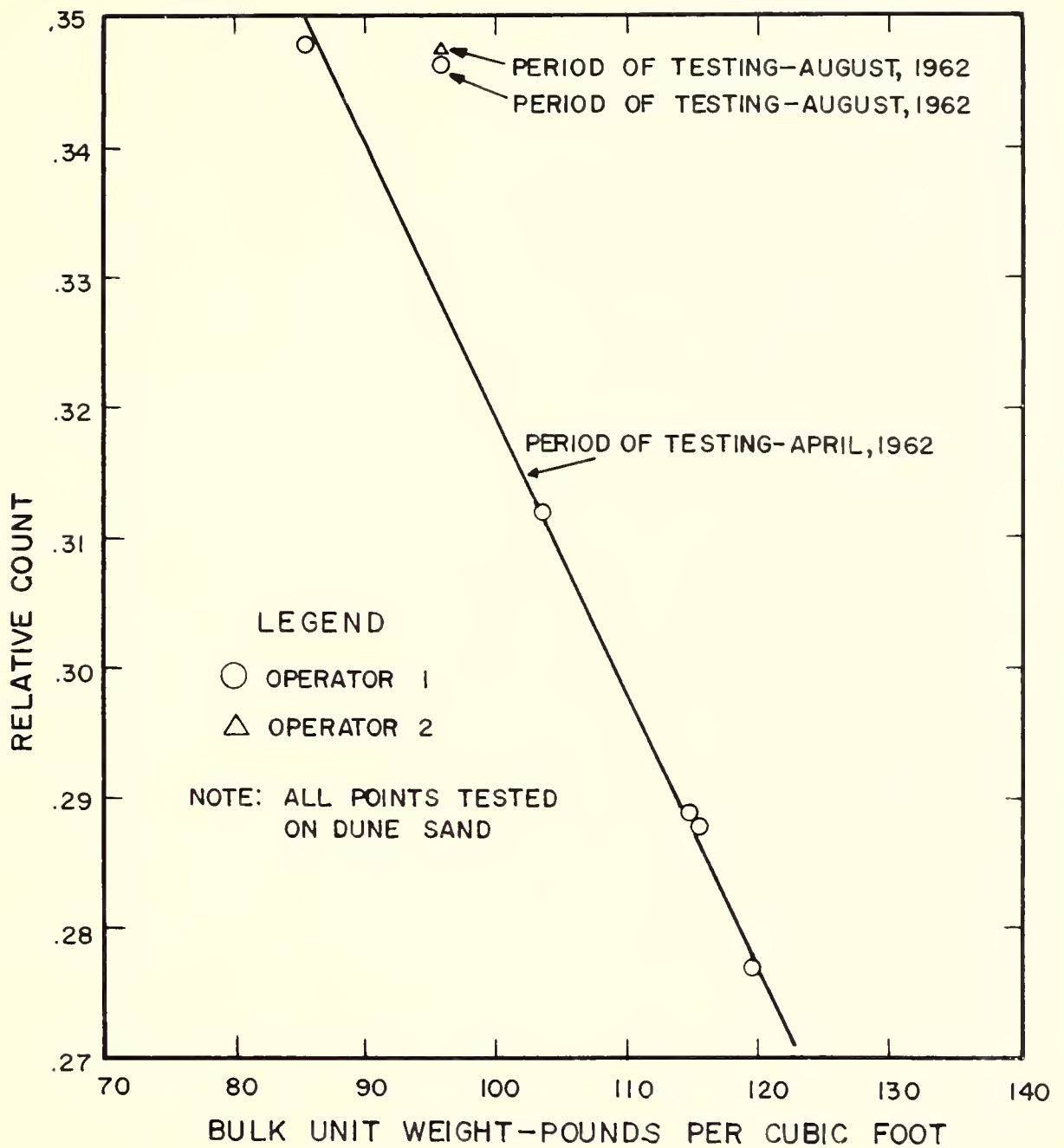


FIG. 28 ILLUSTRATION OF RELATIVE COUNT INCREASE OVER TESTING PERIODS, AND CONSISTENCY OF TESTING PROCEDURES BETWEEN OPERATOR 1 AND OPERATOR 2. NUCLEAR CHICAGO

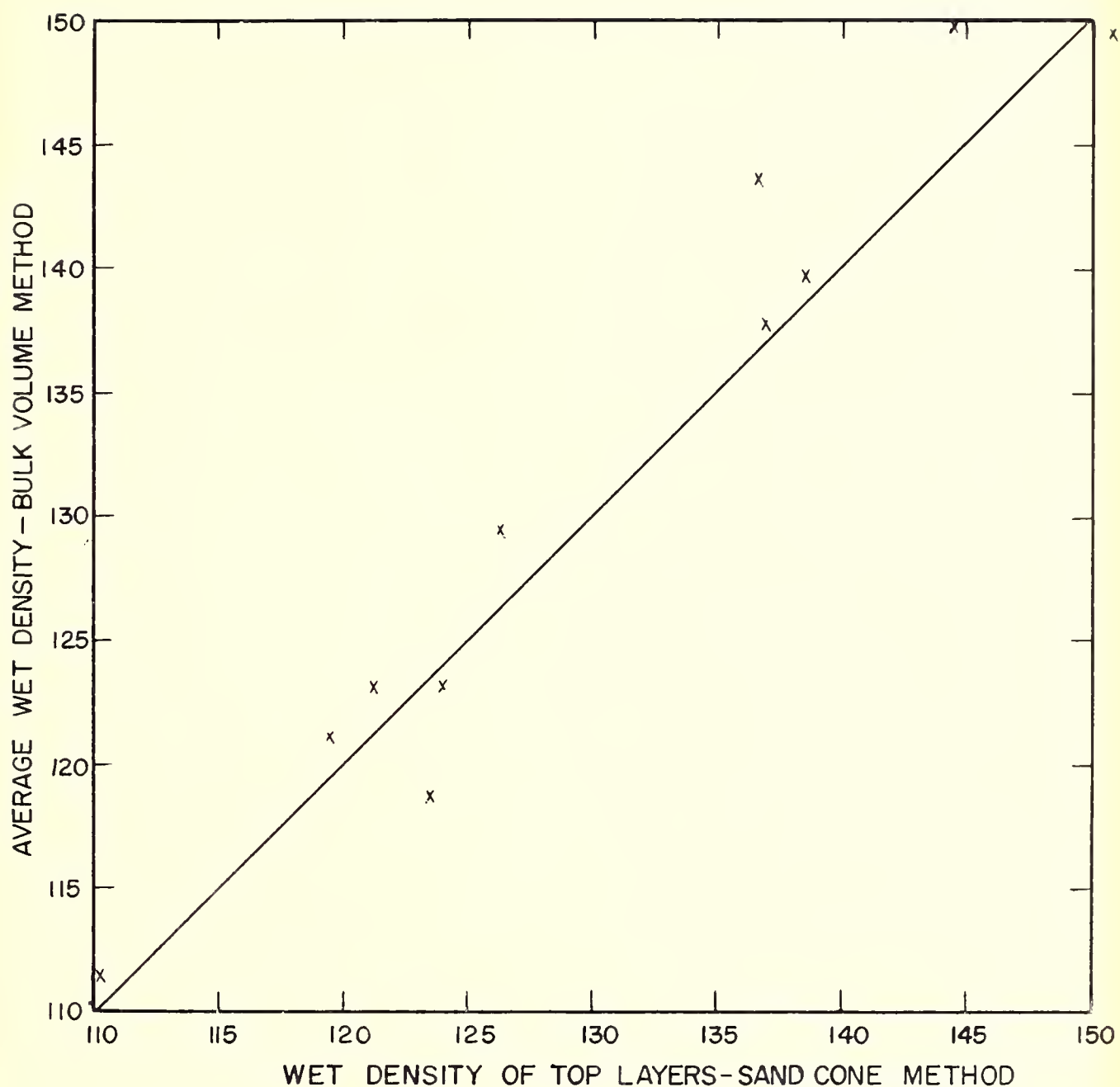


FIG. 29 RELATIONSHIP BETWEEN SAND CONE DENSITY AND CALCULATED BULK-VOLUME DENSITY ON LAYERS TESTED

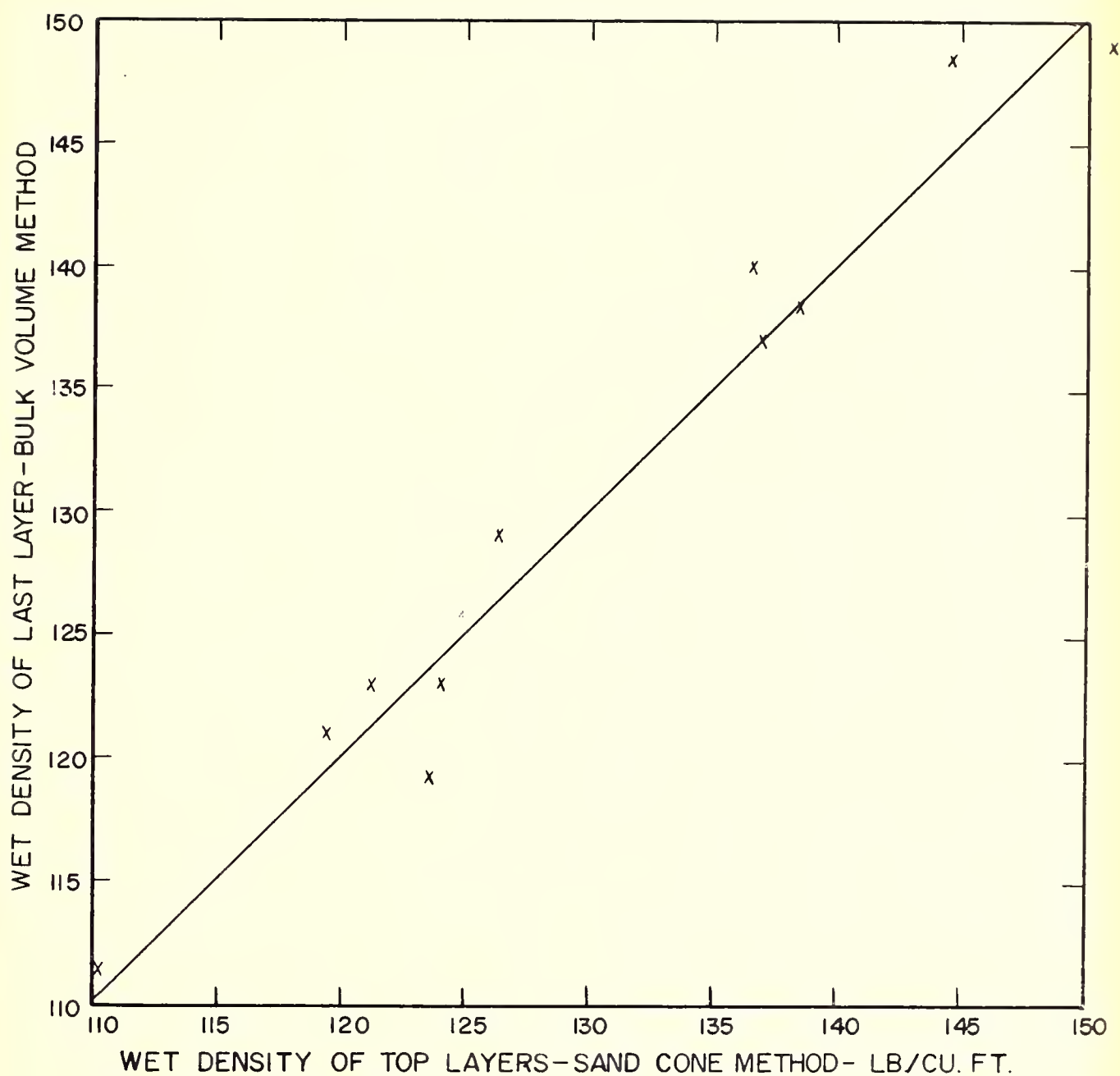
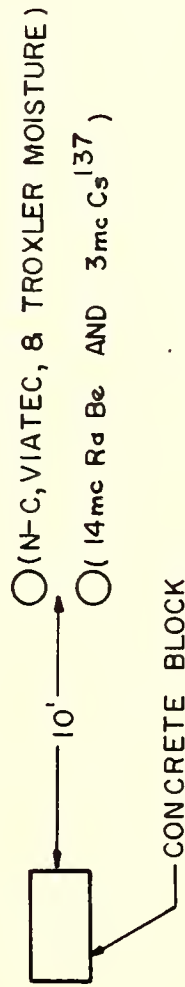


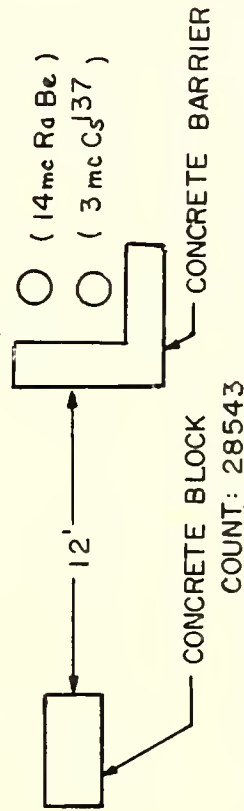
FIG. 30 RELATIONSHIP BETWEEN SAND CONE DENSITY AND CALCULATED BULK-VOLUME DENSITY ON LAST LAYER

(A) COUNTS WITH NO BARRIER



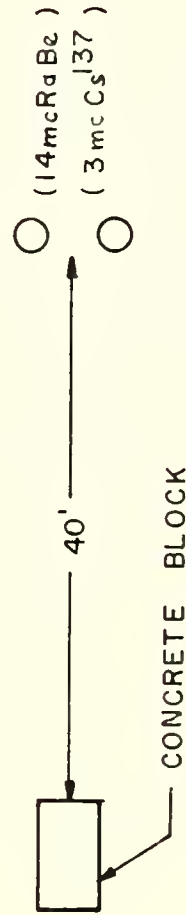
COUNT: 29511

(B) COUNTS WITH OTHER INSTRUMENTS BEHIND BARRIER



COUNT: 28543

(C) ALL OTHER INSTRUMENTS REMOVED FROM AREA OF TESTING



COUNT: 28549

NOTES: A) TEST INSTRUMENTS LEFT IN SAME POSITION DURING (A), (B), (C)
B) COUNTS OBTAINED FROM TROXLER DENSITY PROBE

FIG. 31 EFFECT OF CONCRETE BARRIER ON BACKGROUND RADIATION

